EXPERIMENTAL STUDIES OF IMPULSIVE NOISE PRODUCED BY SPHERES MOVING THROUGH WATER

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THESIS

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PRODUCED BY SPHERES MOVING THROUGH WATER

by

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March 1980

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Experimental Studies of Impulsive Noise Produced by Spheres Moving Through Water

by

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ABSTRACT

It is known from previous experiments that freely falling spheres produce sudden noise bursts. The source of this noise is unknown and little is known about the conditions under which it occurs. In an attempt to study this phenomenon under controlled conditions, spheres were towed in an anechoic tank. Velocities up to 5 m/sec and Reynolds numbers up to 5×10^5 were obtained with spheres of 2", 4" and 10" diameter. After eliminating all mechanical and acoustical disturbances, no noise bursts could be detected. However, the impulsive noise was still observed in free-fall experiments, and a ranging system allowed the location of these noise bursts with respect to a fixed point. A frequency analysis was done with a digital signal processor.

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SYMBOLS AND ABBREVIATIONS

Re - Reynolds Number: $Re = \frac{VD}{\nu}$

S - Strouhal Number: $S = \frac{nD}{V}$

V - Velocity (m/sec)

D - Diameter (m)

ν - Kinematic Viscosity (m^2/sec)

n - Vortex Shedding Frequency (sec^{-1})

°C - Degree Celsius

C_D - Drag Coefficient: $C_D = \frac{\text{Drag}}{\frac{1}{2} \rho_w V^2 A}$

A - Crossectional Area (m^2)

ρ_w - Density of Water (gr/cm^3)

ρ_s - Density of the Sphere (gr/cm^3)

g - Gravity: $g = 9.81\ m/sec^2$

s - Difference in the Different Tracks of the Brush Recording

I. INTRODUCTION

A. HISTORY

The hydrodynamic behavior of bodies moving through fluids has been studied and analyzed in detail for many years. The behavior of bodies, moving with constant velocity, is well known and has been described by Schlichting [1] and others. But, there haven't been many studies of the noise radiated by moving spheres or other bodies.

Richardson [2] investigated the flow and the sound field near a cylinder towed through water. For $Re < 5 \times 10^3$ the flow noise was mostly steady. For higher Re the flow noise was overlaid with irregular fluctuations and noise bursts which increased in magnitude until about $Re = 10^4$.

No experimental data could be found about the noise radiated by a sphere moving through water with constant speed and known Re. Winny [3] observed the air flow around spheres and found a "crackling sound" in the vicinity of $Re = 1.3 \times 10^5$. This sound seemed to be originated near the point of separation of the flow.

Sendek [4] investigated noise bursts radiated by spheres freely falling in water and analyzed the frequency spectra. He found out that those bursts occurred at random times, but were more frequent with increasing velocity and increasing Re.

B. MOTIVATION

The few experiments done up to now left a large number of variables undetermined, but they showed that blunt bodies moving in a fluid produce distinct noise bursts of an apparent hydrodynamic origin. But how and where - with respect to the moving sphere - is this impulsive noise produced? Does the occurrence depend on the velocity or Re? Are there lowest or highest velocities or Re for the development of those noise bursts? And most important, what is the physical mechanism responsible for this phenomenon?

In Sendek's experiments [4], the location of the burst and the Re of the sphere at the moment of the occurrence of the noise bursts were left as unknowns. My goal was to eliminate these unknowns and to analyze the radiated noise with the more modern equipment now available.

II. APPARATUS

A. LOCATION

All experiments were conducted in the anechoic tank in the basement of the Spanagel Hall, Naval Postgraduate School. The dimensions of the tank are:

Length: 714 cm

Width: 163 cm

Height: 219 cm

The bottom and the sides of the tank are completely covered with anechoic material. An anechoic cover for the surface was not available.

The temperature of the water was 20°C throughout all experiments.

B. SPHERES

Six different spheres were used in the experiments. Their properties are listed in Table I.

The terminal velocity and the Re at terminal velocity have been calculated from the fact that at terminal velocity the drag is equal to the weight in water. This results in the formula

$$C_D = \frac{4D^3(\rho_s/\rho_w - 1)g}{3\,\nu^2\,Re^2}.$$

Only Re and the drag coefficient are unknown and they can be found by trial and error from the curve of drag coefficient vs Re in Fig. 1.

For the towing experiments, a head, and/or tail line could be attached to the sphere as shown in Fig. 2.

C. FREE FALL OF THE SPHERE

These experiments had to be done in the beginning to prove that the system was able to record the impulsive noise, described by Sendek [4]. For this reason, no special apparatus was built to release the sphere. It was simply held by hand about 20 cm below the surface and released. To avoid any unwanted disturbances, the sphere and the hand had to be free from air bubbles and the surface of the water had to be nearly motionless.

A net, lowered to the bottom of the tank, was used to recover the sphere.

D. TOWING MECHANISM

1. Towing with a Head Line

The towing system - shown in Fig. 3 - consisted of the following parts:

a. Electric Motor

A 1.5 hp motor, with speed adjustable between 500 and 5000 rpm and with different wheels on which to wind up the towing line. A mechanical transmission with a gear ratio of 1:60 could be connected with a V-Belt and provided an even larger range of speed. By these means, the velocity of the towed sphere could be altered between 0.002 m/sec and 5 m/sec. The motor rested on a foam rubber cushion to prevent vibrations from being transferred from the motor to the tank.

b. Towing Line

Either a threaded steel wire, 1.0 mm diameter, breaking strength 136 kg, or a perlon fishing line, 0.9 mm diameter, breaking strength 45 kg were used for the experiments. A breaking mechanism in the towing line above the water - as shown in Fig. 4 - prevented breaking of the line underneath the water at the end of the run or if too much force was applied.

c. Pulleys

The towing line was led over two 10 cm plastic pulleys with teflon bushings.

d. Clamp

A metal clamp held spheres up to 10.1 cm diameter firmly in start position.

e. Funnel

A metal funnel with foam rubber cushion caught the sphere at the end of the run. The sudden stop caused the breaking mechanism in the towing line above the water to part.

2. <u>Towing with a Head and Tail Line</u>

This towing system is shown in Fig. 5. The difference from the previously described system is the closed loop of the towing line and the replacement of the clamp by two other pulleys.

E. RANGING SYSTEM

1. Hydrophone Array

Four Atlantic Research LC 10 hydrophones were installed in a frame as shown in Fig. 6. The frame was made from 1"-nylon tubes with holes to hold the hydrophones. The hydrophones were located at the four adjacent corners of a "one-meter cube."

2. Computing the Location

Because the real time of the noise burst was unknown, its location had to be determined from the three arrival time differences between the three outer and the center hydrophone.

The method of computation is shown below:

t_i	=	arrival time of the signal at the hydrophone.
x,y,z	=	location of the noise burst with respect to the center hydrophone.
a	=	distance from the center hydrophone to the outer ones.
c	=	speed of sound in water.

The hydrophones are located at (0,0,0), (a,0,0), (0,a,0) and (0,0,a).

$$r^2 = x^2 + y^2 + z^2$$

$$T_1 = c(t_0 - t_1) = r - \sqrt{(x-a)^2 + y^2 + z^2}$$

$$T_2 = c(t_0 - t_2) = r - \sqrt{x^2 + (y-a)^2 + z^2}$$

$$T_3 = c(t_0 - t_3) = r - \sqrt{x^2 + y^2 + (z-a)^2}$$

and after some rearrangements:

$$r = \frac{T_1^2 - a^2 + 2ax}{2T_1}$$

$$y = \frac{a^2 - T_2^2 + 2\,T_2\,r}{2a}$$

$$z = \frac{a^2 - T_3^2 + 2\,T_3\,r}{2a}$$

$$x = \sqrt{r^2 - y^2 = z^2}$$

After starting the computation with a guessed value for x, some iterations gave the three coordinates in the desired accuracy. But the method fails, if x is less than zero. The calculation was done on a Wang computer, Model 2216/2217.

The program is listed below:

```
10 SELECT PRINT 213 (64)
20 INPUT T1,T2,T3
30 PRINTUSING 40, T1, T2, T3
40% T1=##.######     T2=##.######     T3=##.######
50%  X=###.##         Y=###.##          Z=###.##
60 D=.1
70 X=T1*200000+50
80 C=150000
90 T1=T1*C
100 T2=T2*C
110 T3=T3*C
120 A=100
130 R=(T1*T1-A*A+2*A*X)/(2*T1)
140 Y=(A*A-T2*T2+2*T2*R)/(2*A)
150 Z=(A*A-T3*T3+2*T3*R)/(2*A)
160 SELECT PRINT  005(64)
170 W=(R*R-Y*Y-Z*Z)
180 IF W [ 0 THEN 330
190 X1=SQR(W)
200 PRINT X1
210 E=X-X1
220 E=E*E
230 IF E[ 0.5 THEN 360
240 IF T1 [ 0 THEN 300
250 IF X1 [ X THEN 280
260 X=X-D
270 GOTO 130
```

```
280 X=X+D
290 GOTO 130
300 IF X1 [ X THEN 260
310 X=X+D
320 GOTO 130
330 X = X-D
340 D = D/10
350 GOTO 310
360 SELECT PRINT 213(64)
370 PRINTUSING 50, X,Y,Z
380 PRINT
```

F. SYSTEM FOR RECORDING, REPLAY AND ANALYSIS

See Fig. 7.

1. Four-Channel Recording/Replay System

a. Hydrophones

For each channel an Atlantic Research LC-10 hydrophone was used. Properties: The hydrophones have a useful frequency range from 0.1 to 120,000 Hz and they show a nearly flat frequency response between 0.1 and 25,000 Hz.

b. Amplifiers

Two Hewlett Packard Type 465 A amplifiers in series provided a gain up to 80 dB. They didn't contribute to the background noise, because their noise level was well below that of the tape.

c. Filters

A Spencer Kennedy Laboratories "Variable Electronic Filter Model 302" was used as a high pass filter. It was set to 2 kHz to cut off unwanted low frequency background noise. This limit was chosen, because former studies and experiments had shown that the peaks of the impulsive noise bursts were between 3 and 20 kHz.

d. Tape Recorder

Each run was recorded on a four-channel Precision Instrument 6200 tape recorder. The recording speed was 37.5 ips, which gave a flat frequency response between 0.3 and 100 kHz. In the first experiments, the direct recording mode and 40 dB amplification was used. To improve the signal to noise ratio, 80 dB amplification and the FM-recording mode was used throughout all later experiments. The only disadvantage of this mode was the necessity to cut off the output frequency at 10 kHz, because the carrier frequency for the recording speed 37.5 ips was 50 kHz. But this could be done, because previous experiments had shown that the noise bursts had their largest strength at frequencies below 10 kHz. The recording could be replayed with either 37.5 ips, 3.75 ips or 0.375 ips. The medium speed of 3.75 ips was ideal for the acoustical and the visual observation of the run. The speed of 0.375 ips was used in connection with the Brush recorder and the digital signal processor.

e. Oscilloscope

An oscilloscope, type Fairchild Dual Beam 777, was used to monitor the input and the output of the tape recorder. Observation of the input signal showed if any noise of other experiments in the building was interfering with the experiments. Observation of the output helped to distinguish the noise bursts from the background noise.

f. Power Amplifier and Loudspeaker

A Hewlett Packard 462A power amplifier in connection with an Advent loudspeaker also helped in finding the noise bursts and distinguishing them from the background noise and other distortion signals, like noise produced by the towing line or by the pulleys.

2. Analysis System

a. Brush Recorder

A two channel recorder, type Clevite Brush Mark 220, was used to record the runs where noise bursts had occurred. For this recording, the tape speed had to be set to 0.375 ips. The Brush recorder set at a speed of 5 mm/sec gave a good view over the whole run. With its maximum speed of 125 mm/sec, the single noise burst could be "blown up" for comparison between the four different hydrophones and to measure the time differences in the arrival times. These differences could be measured with an accuracy of ±0.1 mm, which corresponds to ±8 μsec in time or to ±1.2 cm in distance under water.

c. Frequency Analysis

In the "A-1024" mode, the "Digital Signal Processor SD 360" was used to show the frequency spectrum of a single noise burst. This spectrum was plotted by a Hewlett Packard 7035 B X-Y Recorder.

d. Time-Frequency History of the Noise Bursts

The "Real Time Analyzer SD 335" in connection with the "Spectogram Display Counter Model 1351-14" in the "waterfall" mode allowed a presentation of the frequency

spectrum as a function of time. The system was able to store 128 frequency spectra in its memory and to display those on the screen. The time interval between those spectra could be chosen in steps between 15.75 sec and 0.066 sec, depending on the length of the signal to be displayed. Due to the possibility of playing the tape with recording speed, or 1/10 or 1/100 of this speed, the variety of displays was even three times as large.

III. EXPERIMENTAL PROCEDURE AND RESULTS

A. CHECKING THE SYSTEM

To prove the ability and the quality of the system, the solid brass sphere Nr 5 was released under water. The results of this free fall were comparable to those reported by Sendek [4]. A complete analysis of the free-fall experiments will follow later.

B. TOWING WITH A STEEL HEAD WIRE

These experiments were done with the spheres Nr 2, 3 and 6. A minimum velocity had to be exceeded, because the spheres were not neutrally buoyant. When the spheres were towed below this minimum speed, they deviated too far downward and hit the hydrophone array or even the bottom of the tank. This speed was approximately 1 m/sec for the nylon spheres and 2 m/sec for the aluminum sphere.

Runs were made in the Re region between 1×10^5 and 4×10^5. Velocities above 4 m/sec were not possible, because at these speeds the spheres deviated so far from the straight path that they would either hit the sides of the tank or break through the surface.

Noise bursts, moving with the sphere, were recorded and analysis showed some of these bursts to have frequency spectra peaking at 6, 10 or 16 kHz. But other signals showed different frequency spectra and all runs were highly distorted by wire noise and the bursts were quite uncharacteristic of those observed from freely-falling spheres.

Another disadvantage of those experiments was the large deviation of the sphere from the straight path. This made it impossible to determine the location of the sphere at the time where the noise bursts occurred.

C. TOWING WITH STEEL HEAD AND TAIL WIRES

The advantage of a closed-loop towing system, with the towing line under tension, was a better knowledge of the location of the sphere with respect to time. These experiments were done with the spheres Nr 2, 3 and 6 in the velocity region of 0.0038 m/sec to 3 m/sec, corresponding to the Re region of 375 to 2.9×10^5. At all velocities, very sharp, distinct noise signals could be recorded. But further investigation showed that these were not coming from the sphere, but from the pulleys. This noise was produced by the wire slipping sidewards on the pulleys. Runs with a streamlined body, attached to the wire in place of the sphere, produced very similar signals only smaller in amplitude.

D. TOWING WITH A PERLON HEAD LINE

This sytem was hardly usable. At speeds fast enough to keep the sphere off the bottom, the sphere already deviated far from the straight path. In the few runs where the sphere passed relatively straight through the tank, no signals were recorded.

E. TOWING WITH A STEEL HEAD WIRE AND A PERLON TAIL LINE

The closed-loop system provided a nearly straight path of the towed sphere. The perlon line was almost noiseless.

The steel wire was greased to reduce the noise originated at the pulleys.

These experiments were done with the spheres Nr 1 and 2. The large glass sphere was towed with velocities between 0.4 m/sec and 2 m/sec, respectively in the Re region of 1×10^5 to 5×10^5. There was not a single noise burst in any one of all the runs.

More runs were made with the 10.1-cm nylon sphere in the same Re region, but with higher velocities. The sphere moved about 50 cm off the straight path. Distinct noise signals, moving with the sphere, could be recorded. But those were different in shape - on the Brush recording - compared to the ones received in the free-fall experiments. Further investigations brought up that those signals were always appearing when the sphere was moving to the right. The noise was obviously produced by the wire, touching a metal part at one side of the funnel. The translation of those signals from its origin through the wire to the nylon sphere could have led easily to wrong interpreted results.

F. TOWING WITH PERLON HEAD AND TAIL LINE

This system was by far the most quiet one. Only two more disturbances had to be eliminated to bring the background noise of the towing system below the amplitude of the tape noise level, which was 70 mV at 0.375 ips. Sideward slipping of the line on the pulleys could be prevented by carefully lining up all the pulleys and by greasing the towing line.

But with increasing velocity, the tail line, entering the water, produced an increasing noise. This was eliminated by leading the line through a foam rubber cushion on the surface of the water. Runs were made with the spheres Nr 2 and 6. There was absolutely no noise signal to be recorded in the Re region between 5×10^4 and 5×10^5.

G. ACCELERATION OF THE SPHERE

A "Variac" allowed to change the speed of the motor between 0 and 5000 rpm. The runs were made with sphere Nr 2 on the closed perlon loop. The sphere was started from rest and accelerated by turning the "Variac" by hand. Over a four-meter run, final velocities between 1 m/sec and 5 m/sec were reached. There was not a single run in which a noise burst was recorded!

H. FREE FALL OF THE SPHERE

After towing the spheres in all the different ways described above hadn't given any positive results, the decision was made to examine the free fall again. These experiments were done with the metal spheres Nr 4, 5 and 6. The falls of the aluminum sphere were noiseless, and only the experiments with the heavier brass spheres are described.

For the experiments, the sphere was held in the hand about 20 cm below the surface of the water. The surface of the sphere was free from air bubbles. When the surface of the water was calm, the sphere was smoothly released. The whole run was recorded over all four hydrophones of the array.

Several runs were completely quiet, some showed single noise bursts and others had up to 20 clear distinguishable signals during the fall. The time of the fall was about 0.65 sec for the heavier, and about 0.8 sec for the smaller sphere.

IV. ANALYSIS

A. LOCATION OF THE NOISE BURSTS

There were several runs during which a sequence of noise bursts were recorded equally well on all four channels of the tape recorder.

Figs. 8, 9, 10, 11 show the brush recording of one of these runs. The tape speed was 1/100 of the recording speed and the Brush-recorder speed was 5 mm/sec. The vertical scale is 20 mV/div. This recording gives a good overview over a successful run and helps in deciding if the signals are recorded well enough on all four channels.

Figs. 12 to 21 show five of the individual signals of the same run blown up in time with a Brush recorder speed of 125 mm/sec. In these recordings, 12.5 mm on the horizontal time scale correspond to 1 msec. This scale allowed to evaluate the time differences between different hydrophones with an accuracy of ±0.1 mm, respectively ±8 msec. The evaluation of the time differences allowed the calculation of the location of each noise burst with respect to the origin of the hydrophone array. These values are listed in Table II.

Fig. 22 gives the position of origin for those bursts from the previously mentioned run. For comparison, the sphere is sketched in scale. The signals seem to have a random distribution within a nearly vertical column whose diameter is that of the sphere.

The height of the bursts with respect to time is shown in Fig. 23. The signals fit relatively well on a curve that may be the trajectory of the sphere. If this is so, the first group of signals occurs at a velocity of about 2 m/sec, the second at about 3 m/sec and the last at about 6 m/sec. In another run with the 8.9-cm brass sphere, groups of noise bursts were recorded at sphere velocities of 2 and 4 m/sec.

A location of the bursts with respect to the sphere was not possible, because no instrumentation was available to track the sphere over the run.

B. FREQUENCY ANALYSIS

1. Frequency Spectrum

The frequency analysis showed that the single noise burst had a peak in the frequency region between 4 and 10 kHz. The frequency spectra of the previously described bursts are shown in Figs. 24, 25 and 26.

The bandwidth of each signal is always less than 1 kHz. Due to the fact that the tape recorder had a cutoff frequency of 10 kHz, it was not possible to observe and to analyze the frequency region above this value.

2. Time History of the Frequency Spectrum

The "waterfall" display gave a complete time history of the frequency spectrum of the whole run. Fig. 27 shows that the run - used as an example throughout this analysis - had four clearly distinguishable groups of noise bursts. Each of this group covered a different frequency region. The

"blown up" time history of each one of the groups is given in Figs. 28 to 31. The analysis of the single groups gives an average lifetime of 170 msec for the first and the third group, and of 120 msec for the other two groups, which contain higher frequencies.

Each group consists of several signals which are only very small time differences apart from each other. The Brush recording showed the single bursts clearly separated from each other, whereas the "waterfall" display gives the picture of a closed group in which different frequencies rise and vanish at different times.

V. DISCUSSION OF THE RESULTS

The first goal of the experiments was to locate the impulsive noise with respect to the towed sphere. This result would have brought the knowledge at which velocities and Re the noise bursts occur and if they were originated at the surface of the sphere or in any part of its wake.

But not a single noise burst could be detected, although the system was able to record the signals from the freely falling spheres, and although the noise level of the towing system was lower in amplitude than the noise level of the tape itself. Even the accelerated sphere didn't produce the expected impulsive noise.

The only difference between the towed and the freely falling sphere was the constraint due to the towing line under tension. But because the source of the noise bursts is still unknown, no theory can be made why these signals appear in the free fall, but not when the sphere is towed. Fig. 23 shows the location of the signals with respect to time. All the signals lie close to the curve which seems to reproduce the accelerated motion of the sphere. This shows that the bursts may either originate at the surface of the sphere or in the wake in a nearly constant distance from the sphere. But this question could not be answered because the towing experiments hadn't given any positive results and because the free fall experiments allowed a location of the noise bursts with respect to a fixed point only.

The frequency analysis showed that the spectra of the noise are rather random in a frequency region above 4 kHz. Each group of noise bursts contains several peaks at different frequencies, starting and decaying at different times. No regularity or repetition could be found. But a complete frequency analysis wasn't possible, because the cutoff had to be set at 10 kHz in the FM-recording mode.

The "waterfall" display showed something that wasn't detected with the Brush recording: The 21 signals, clearly distinguishable in the Brush recording (Figs. 8 to 11), formed three strong and one weak group of signals in the "waterfall" display (Fig. 27).

Calculation of the Strouhal Number with the average velocities and time intervals between the three strong groups of signals resulted in values of S = 0.26 and S = 0.18. Considering the fact that not very much is known about the hydraulics of an accelerated sphere, these values are relatively close to the Strouhal Number S = 0.21 for a cylinder with comparable Reynolds Number. This could mean that the impulsive noise is either originated by the separation bubble, fluctuating with the vortex shedding frequency, or is originated by the vortex itself in the wake of the sphere.

Table I

The Spheres

Number	Material	Diameter (cm)	Weight (gr)	Density (gr/cm^3)	Terminal Velocity (m/sec)	Re
1	glass - (waterfilled)	25.4	10432	1.22	2.29	5.7×10^5
2	nylon	10.1	637	1.20	0.74	7.3×10^4
3	nylon	4.9	74	1.20	0.52	2.5×10^4
4	brass	10.1	4564	8.46	8.70	8.6×10^5
5	brass	8.9	2920	7.91	8.73	7.6×10^5
6	aluminum	10.1	1496	2.77	2.73 5.06	2.7×10^5 5.0×10^5

Table II

Location of the Noise Bursts from the Origin

Burst	Difference on the Brush Recording (mm)			Time Difference (msec)			Position (cm)			time (sec)
	s_1	s_2	s_3	t_1	t_2	t_3	x	y	z	
a	+6.2	-0.3	-0.8	0.496	-0.024	-0.064	125.7	44.9	36.2	0.0
b	+6.2	-0.4	-1.2	0.496	-0.032	-0.096	121.0	43.5	29.9	0.049
c	+5.2	-0.2	-0.8	0.416	-0.016	-0.064	108.1	47.0	37.6	0.079
d	+4.5	-0.8	-0.9	0.360	-0.064	-0.072	94.6	39.0	37.6	0.148
e	+4.4	-0.5	-1.8	0.352	-0.040	-0.144	91.4	43.5	25.0	0.184
f	+3.8	-0.2	-1.1	0.304	-0.016	-0.088	88.2	47.4	35.1	0.200
g	-1.4	-0.4	-1.6	-0.112	-0.032	-0.128	37.0	46.6	34.9	0.354
h	-2.0	-0.5	-1.5	-0.160	-0.040	-0.120	31.2	45.8	36.4	0.367

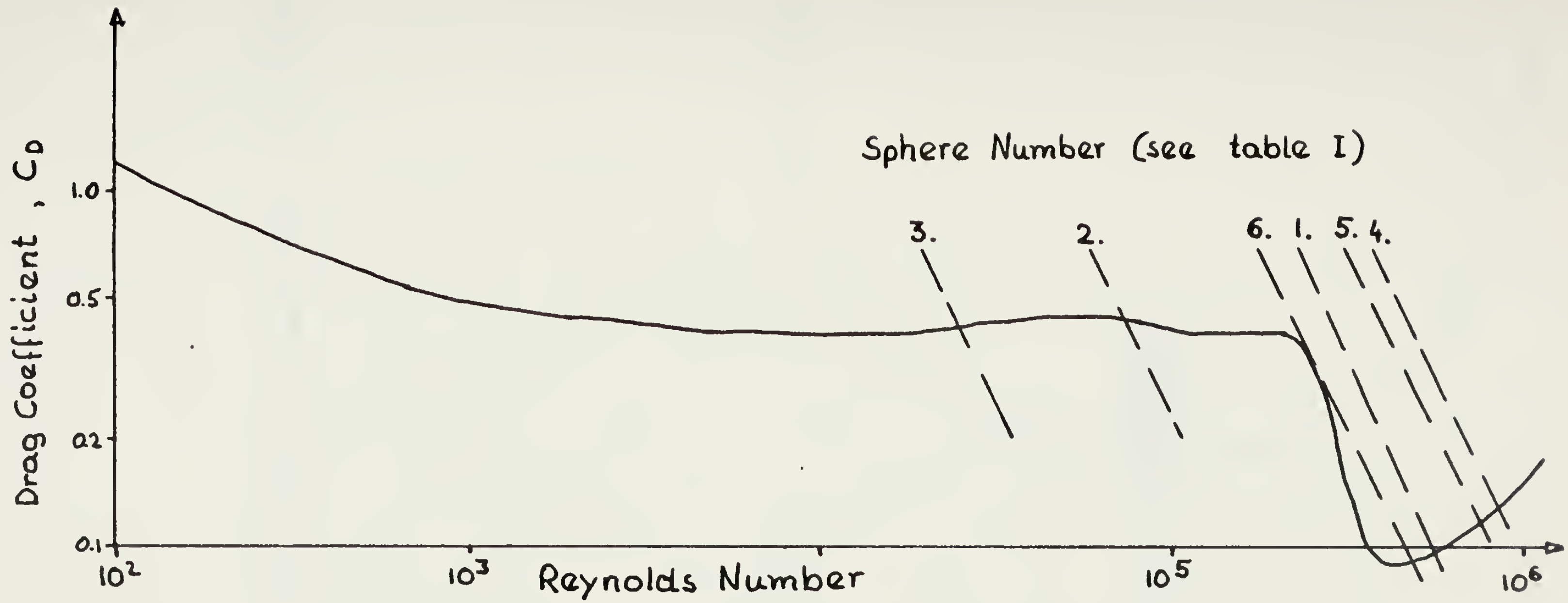

Figure 1. Reynolds Number for terminal velocities

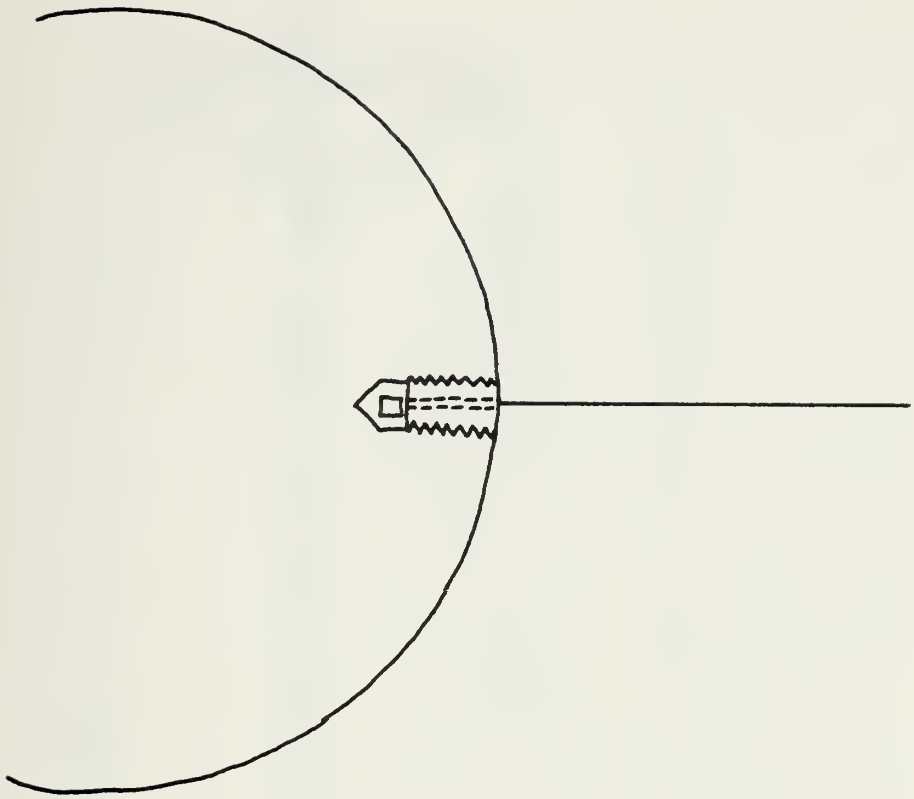

Figure 2. Attachment of the towing line to the sphere

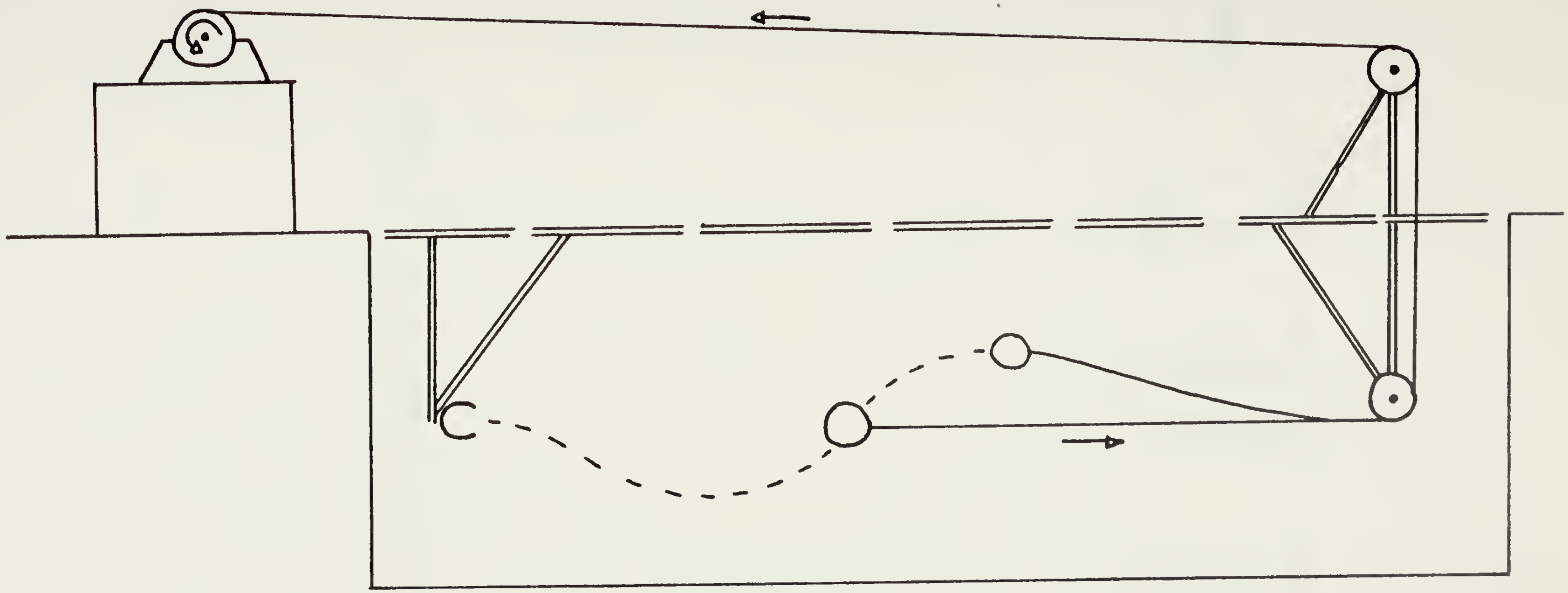

Figure 3. Towing with a head line

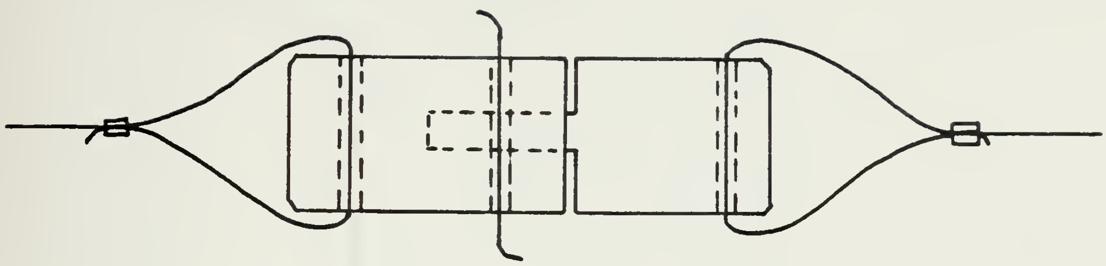

Figure 4. The breaking mechanism, consisting of two fitting steel parts and a copper pin

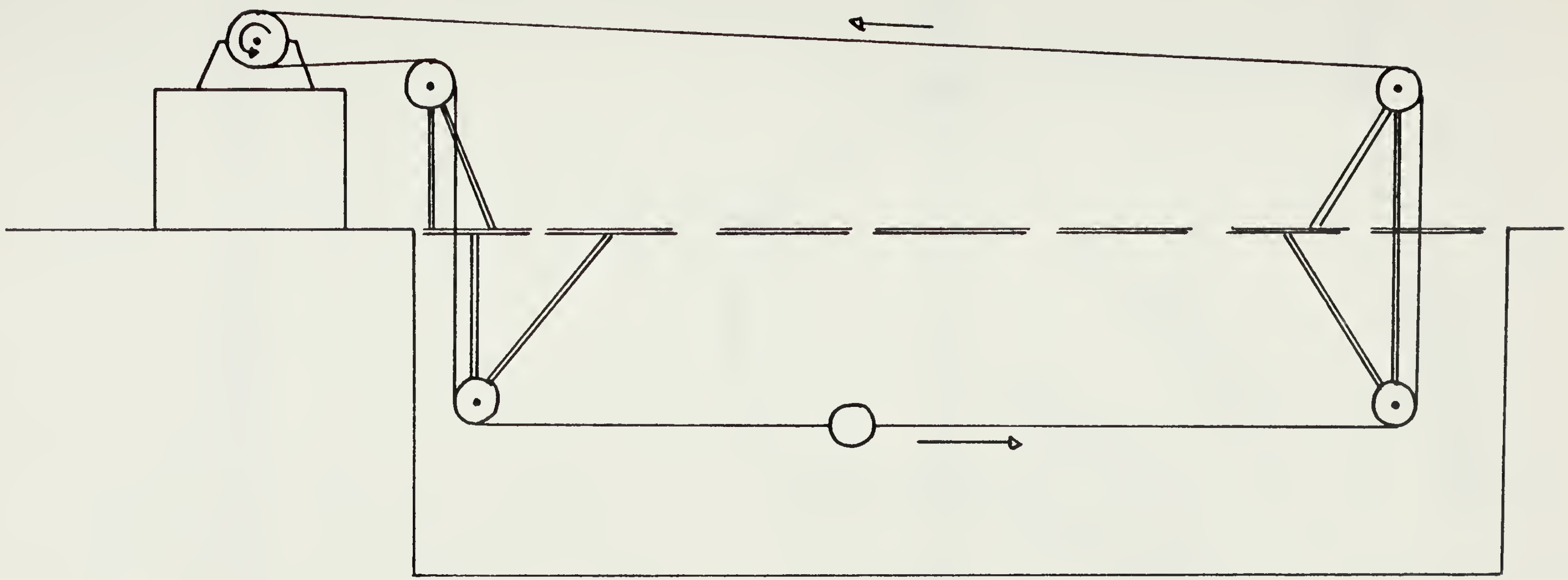

Figure 5. Towing with a head and a tail line

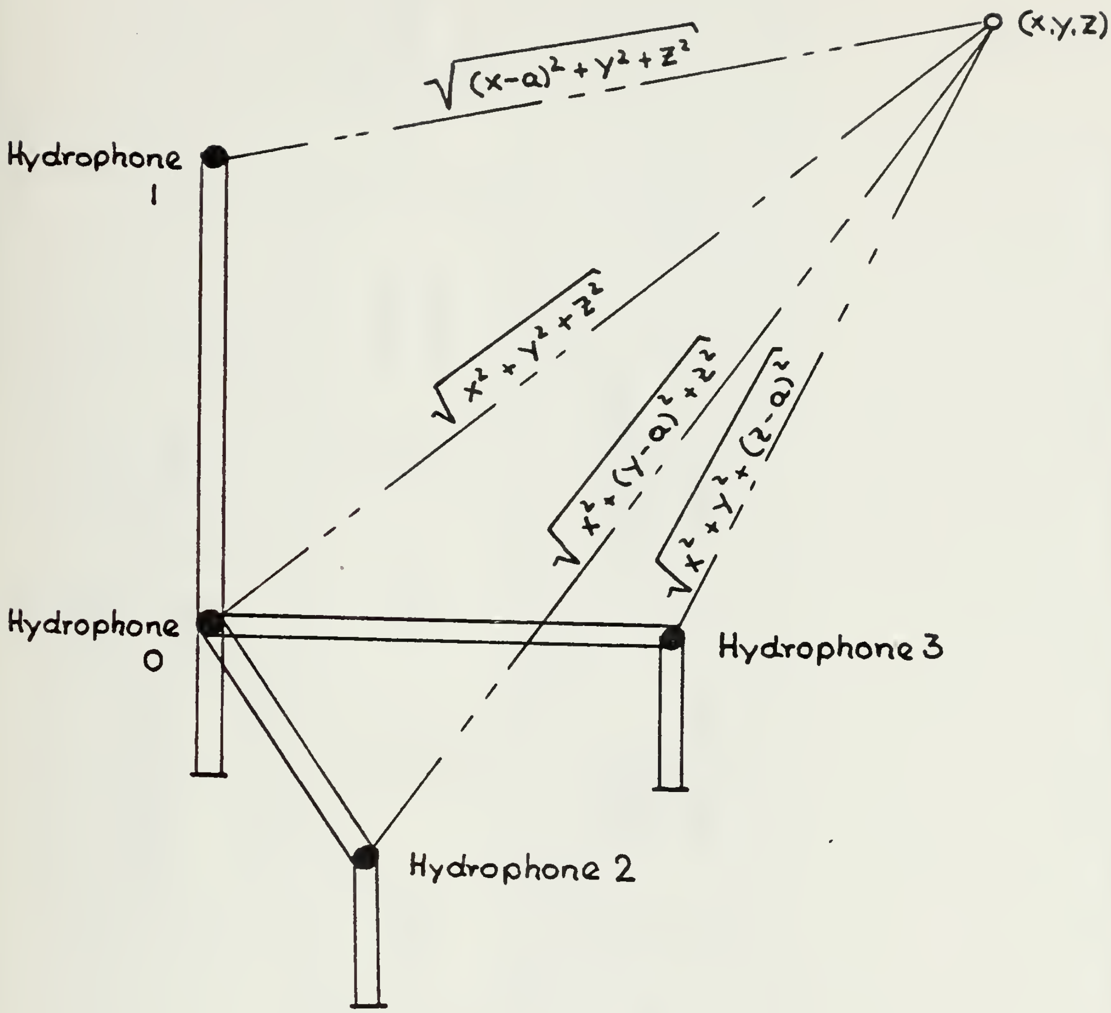

Figure 6. The hydrophone array and the coordinate system for the calculation

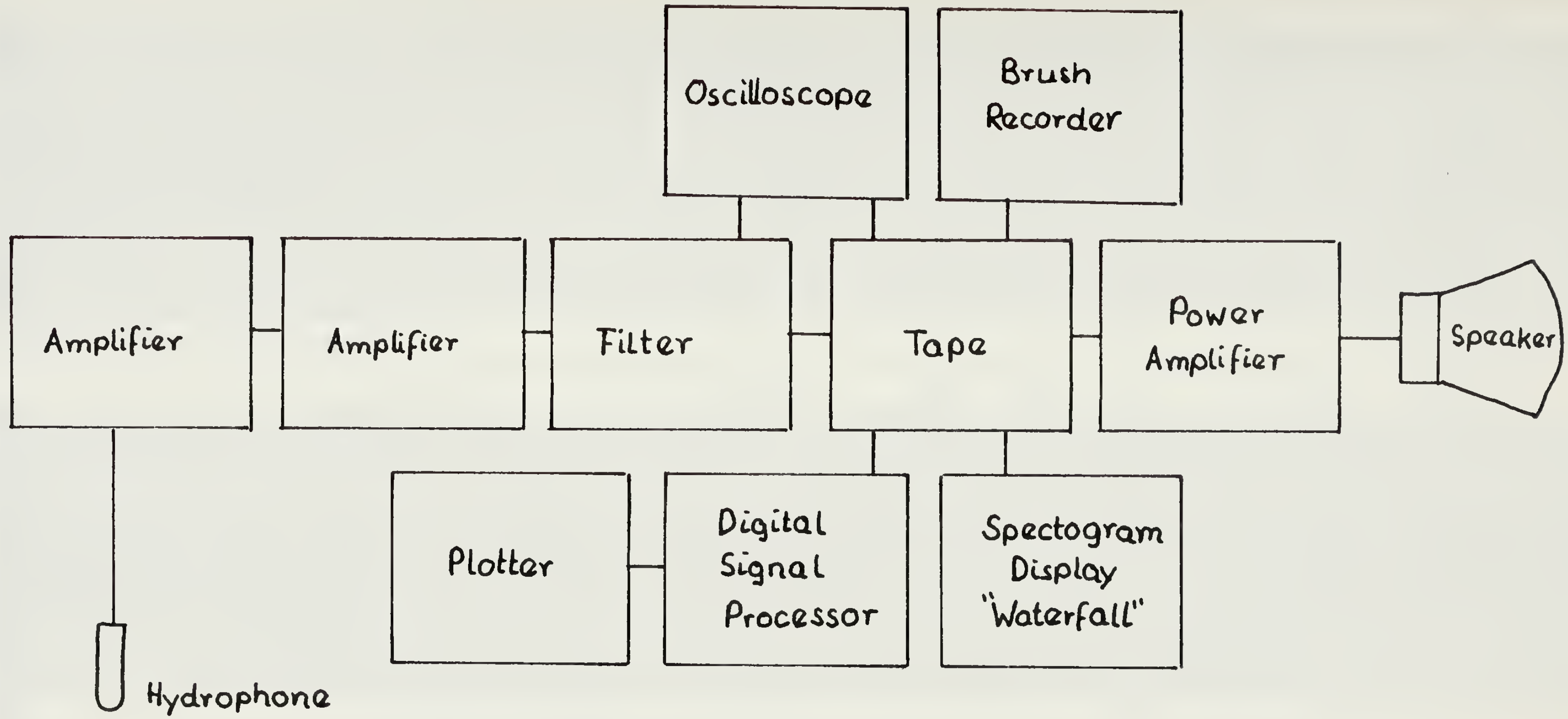

Figure 7. One of the four equal recording/replay/analysis channels

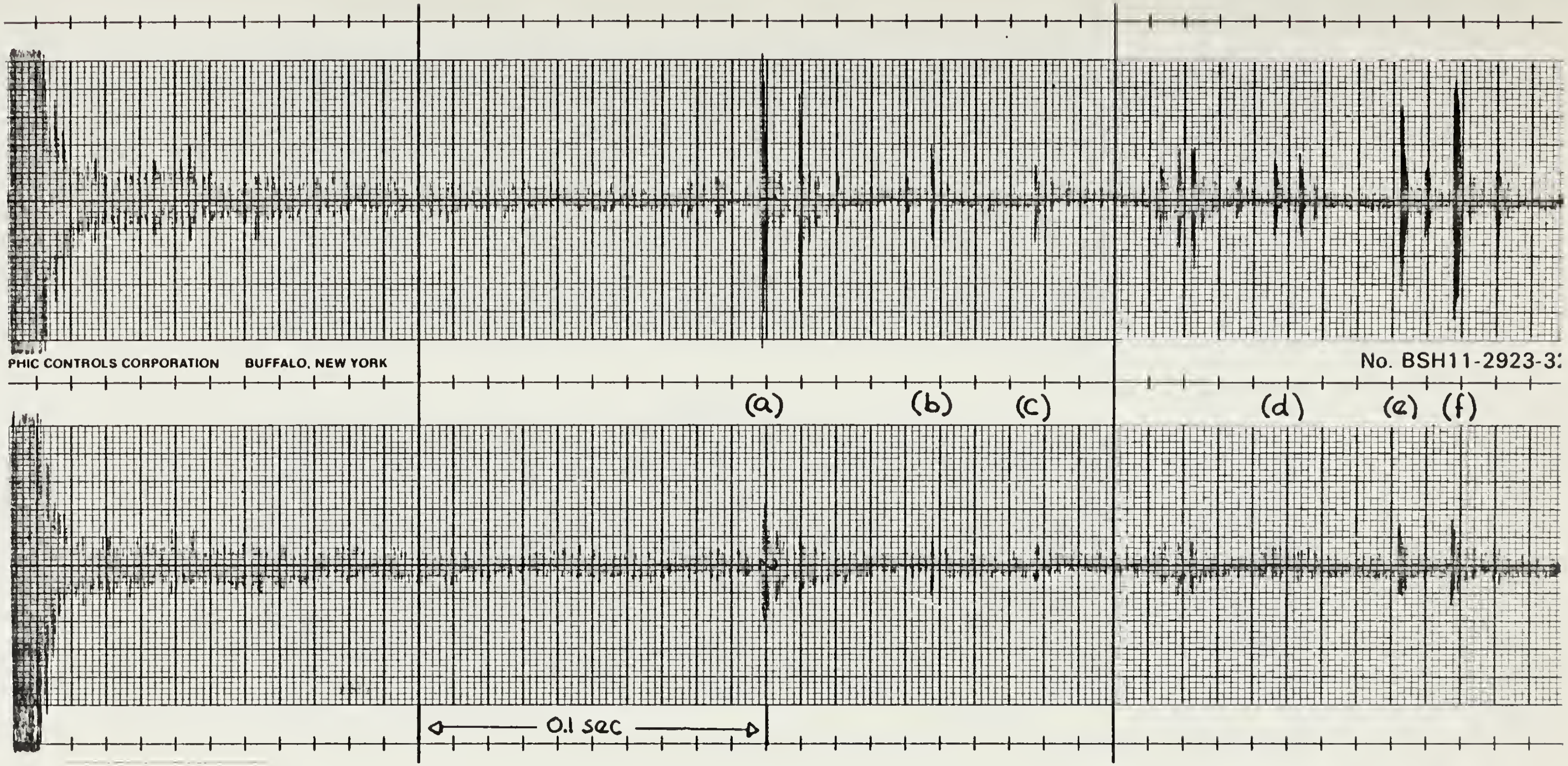

Figure 8. Signal output for the first part of the best run. On the left is the signal from a light tap on the tank cover denoting the start of the run. This run continues on Fig. 9. Letters identify bursts. The upper track is from hydrophone 1, the lower one from hydrophone 0

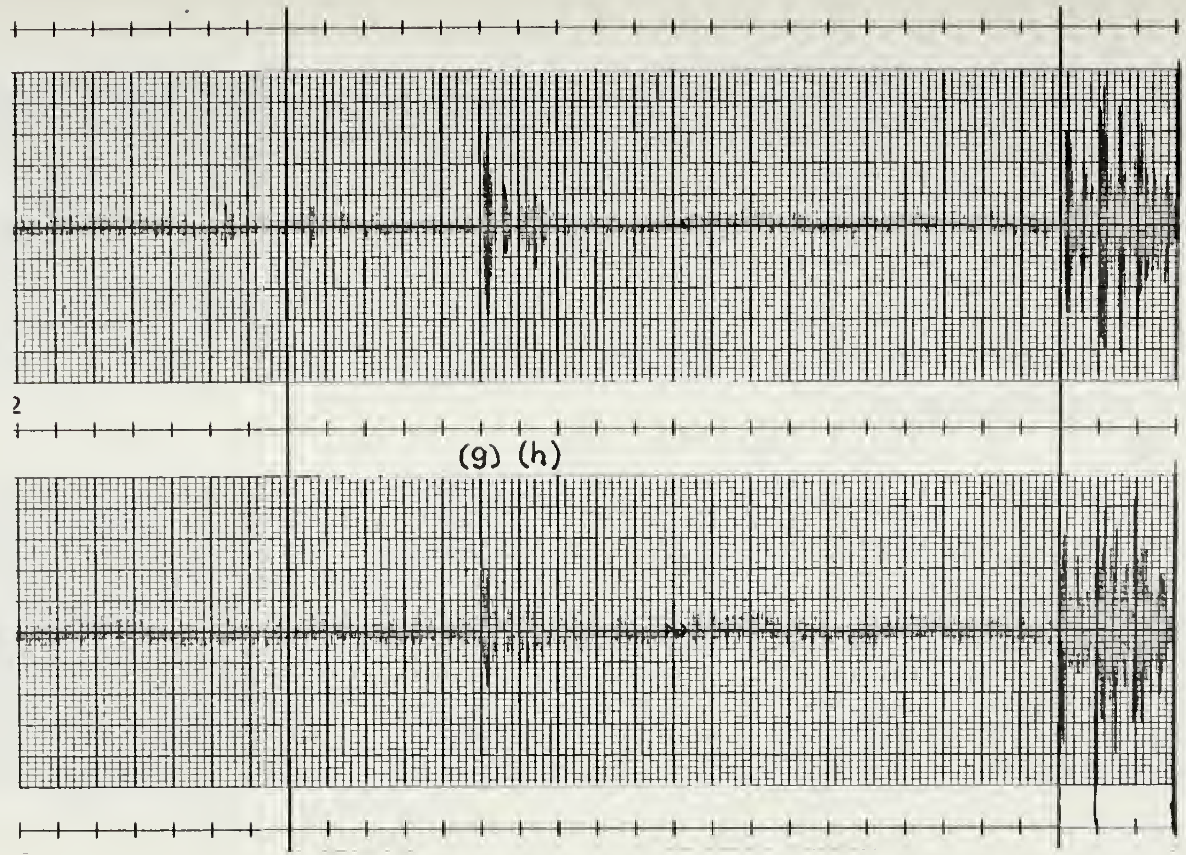

Figure 9. Brush recording of the remaining part of the run whose beginning is shown in Fig. 8. The signal on the right is the noise from the sphere hitting the bottom of the tank.

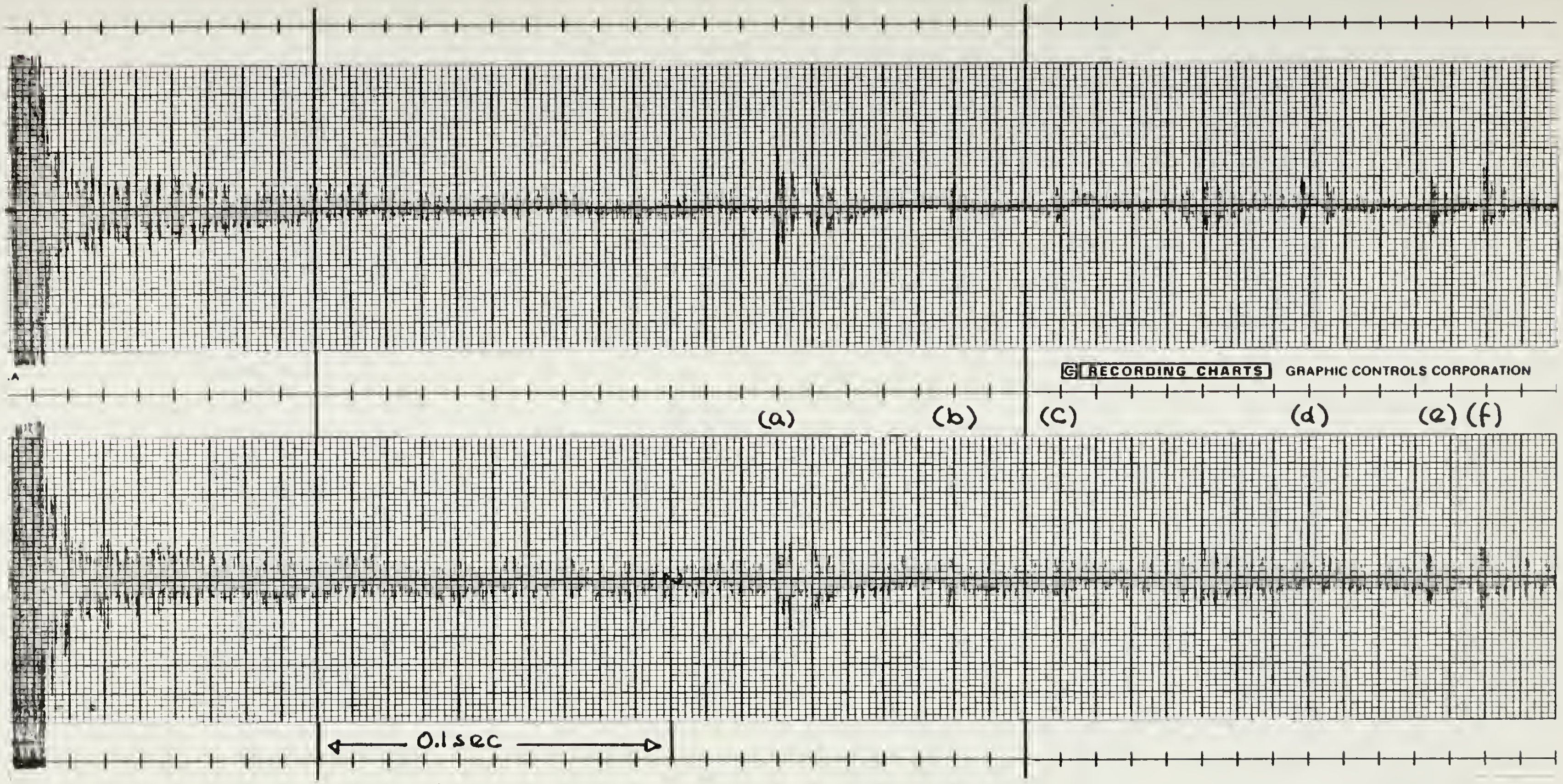

Figure 10. Same as in Fig. 8, but here the upper track is from hydrophone 2 and the lower track is from hydrophone 3

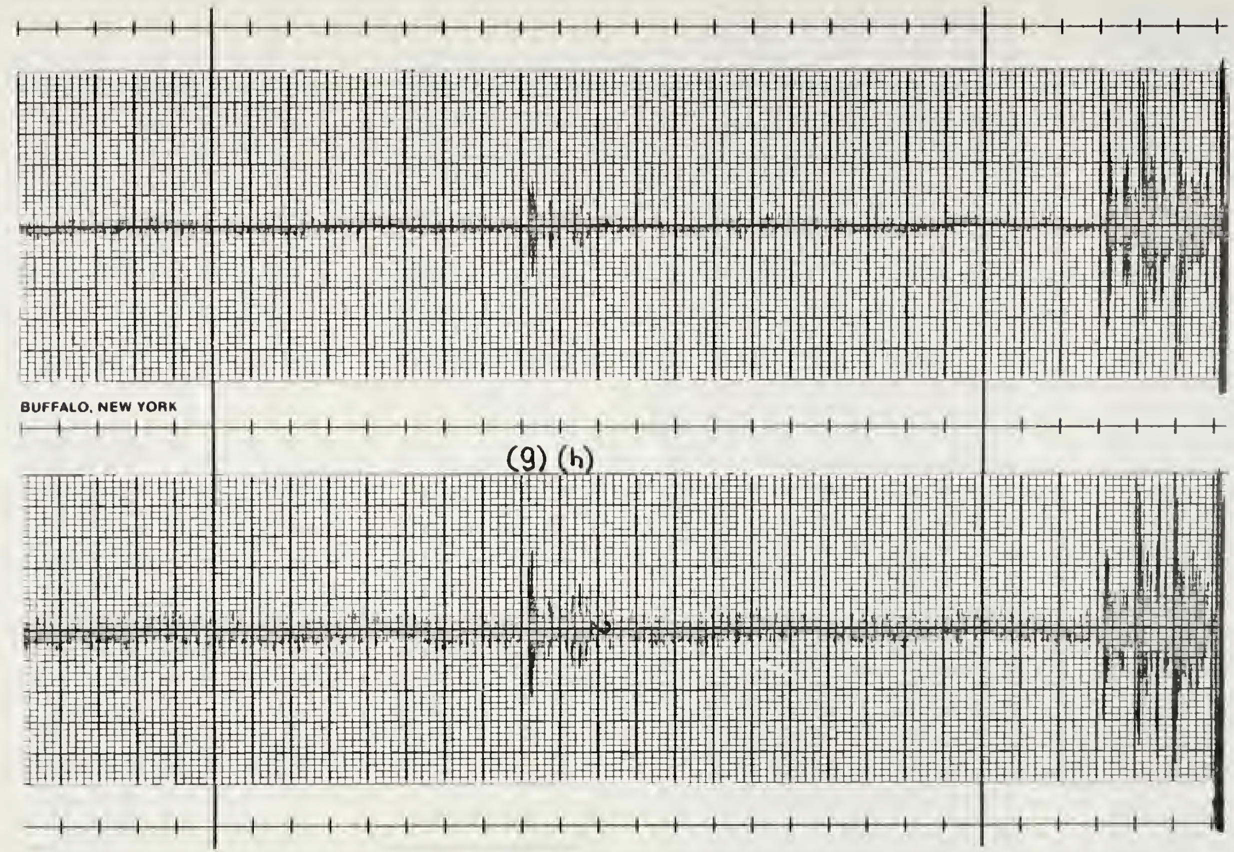

Figure 11. Brush recording of the remaining part of the run whose beginning is shown in Fig. 10

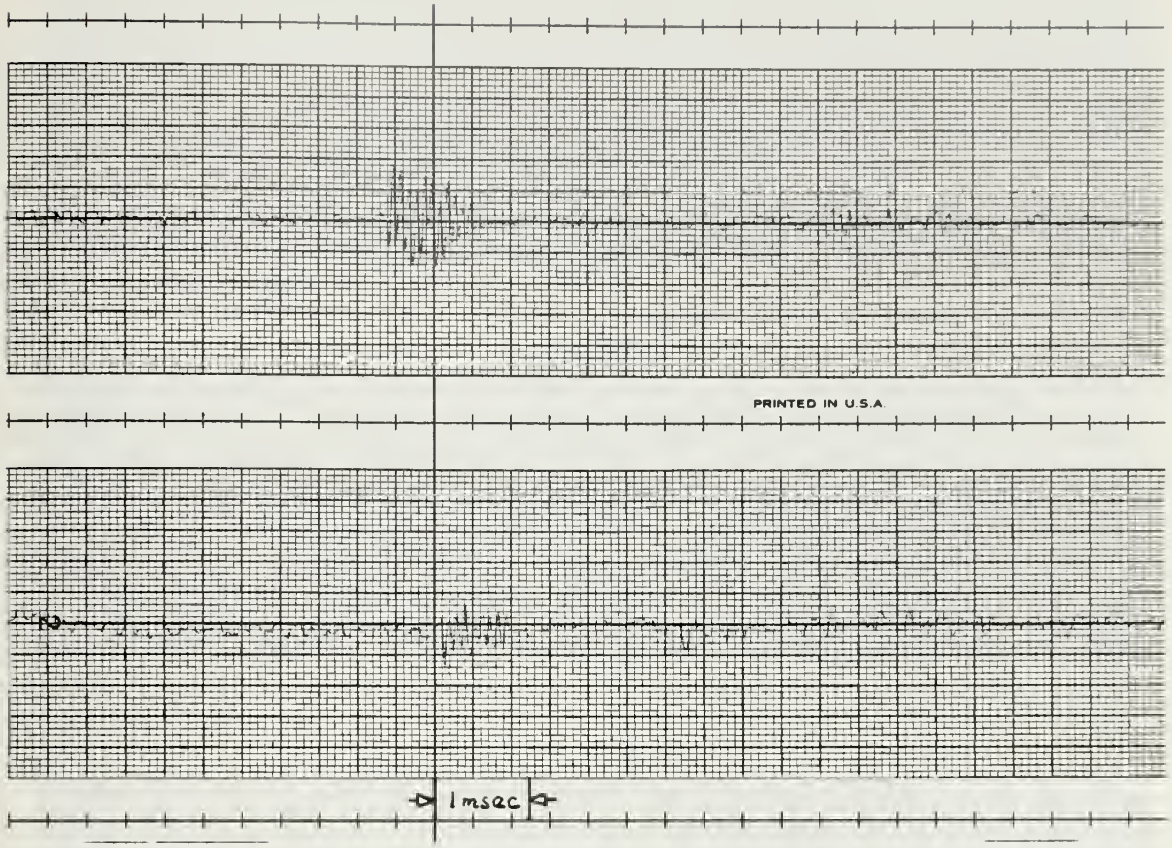

Figure 12. Expanded view of burst (b).
Upper track: Hydrophone 1
Lower track: Hydrophone 0

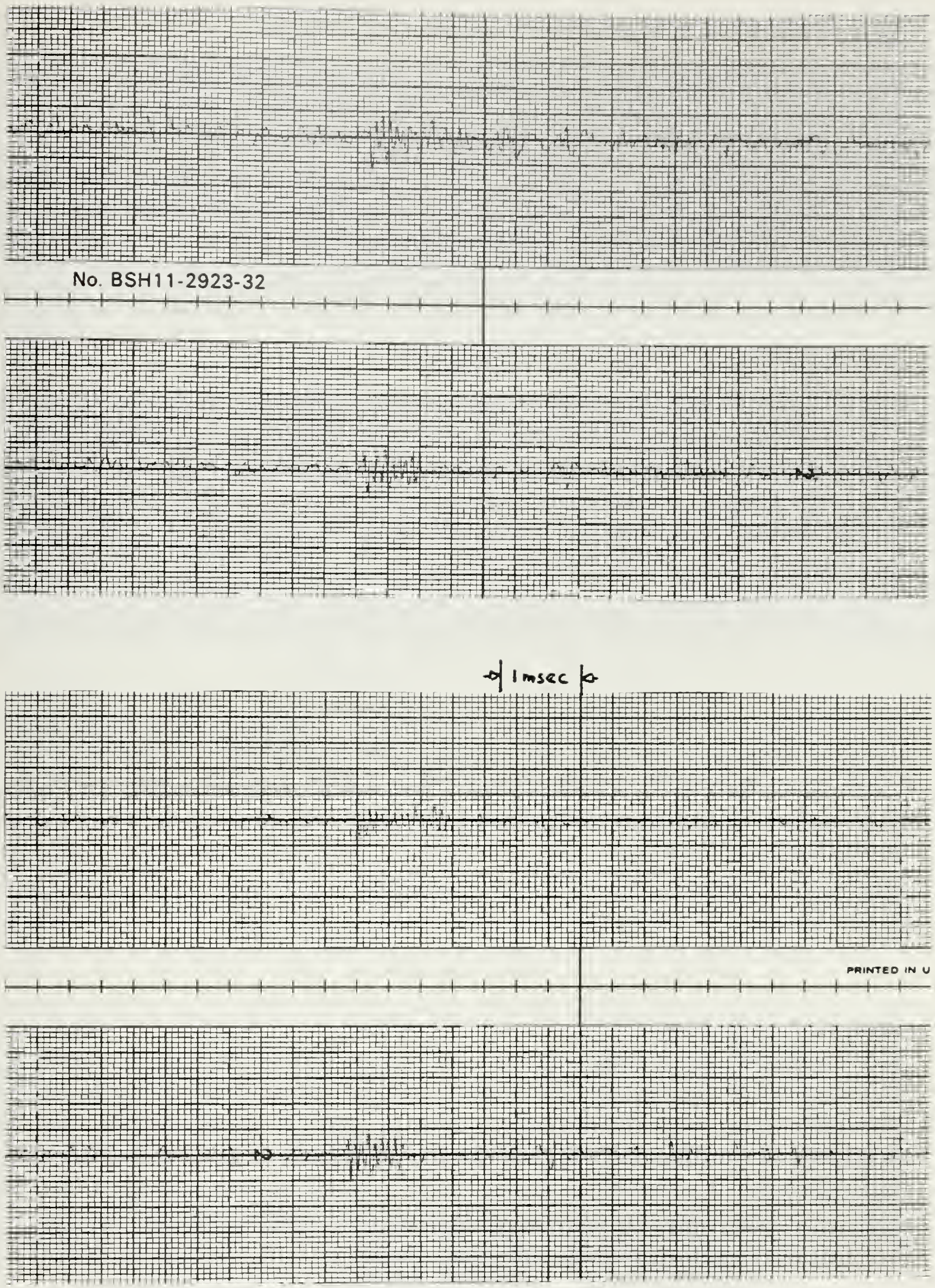

Figure 13. Expanded view of burst (b).
First track: Hydrophone 2.
Third track: Hydrophone 3.
Second and fourth track: Hydrophone 0

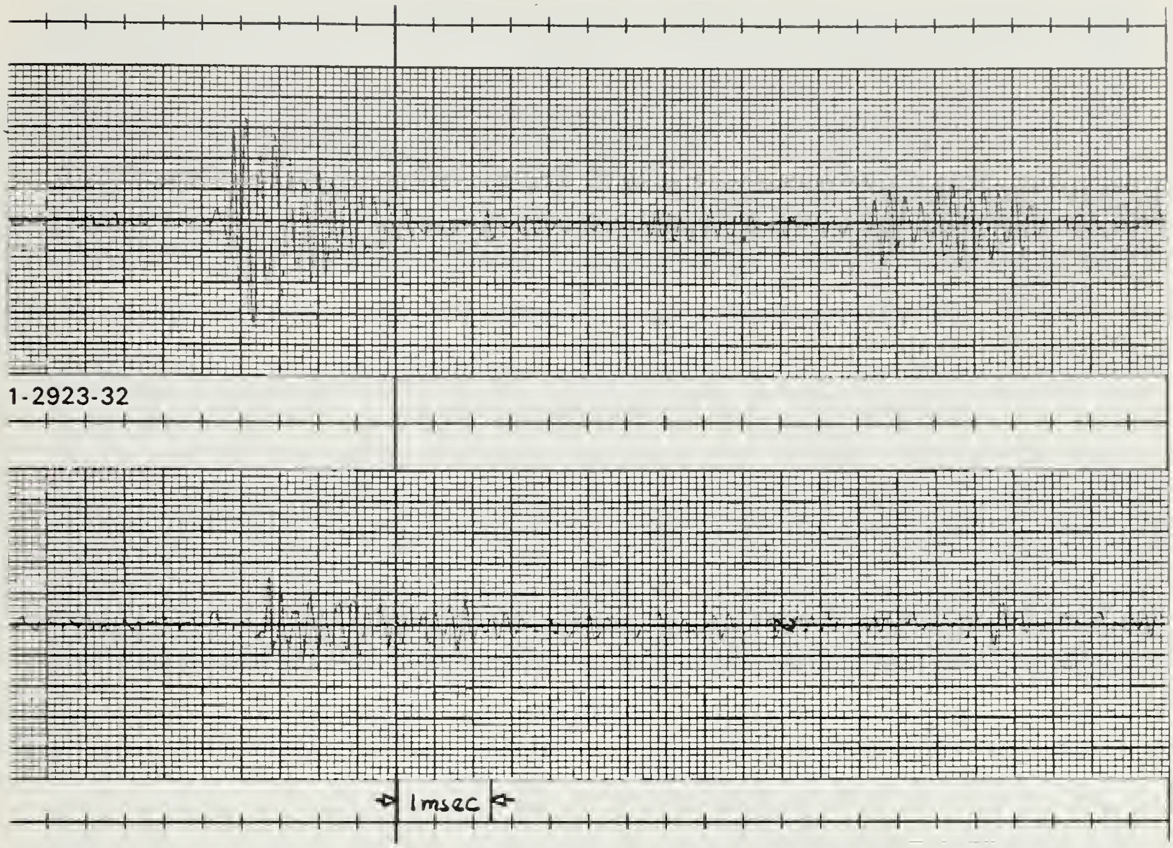

Figure 14. Expanded view of burst (e)
Upper track: Hydrophone 1
Lower track: Hydrophone 0

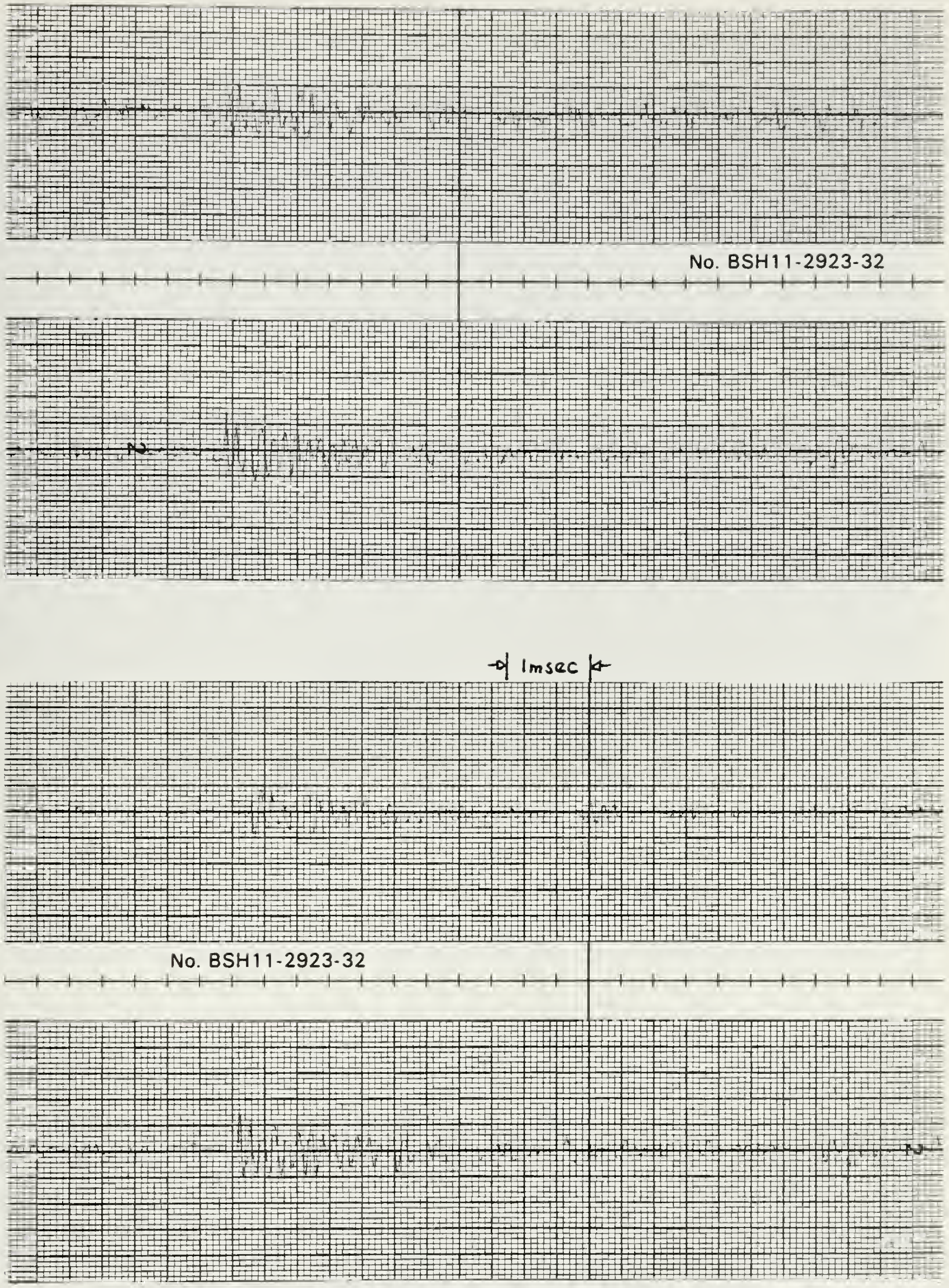

Figure 15. Expanded view of burst (e).
First track: Hydrophone 2.
Third track: Hydrophone 3.
Second and fourth track: Hydrophone 0

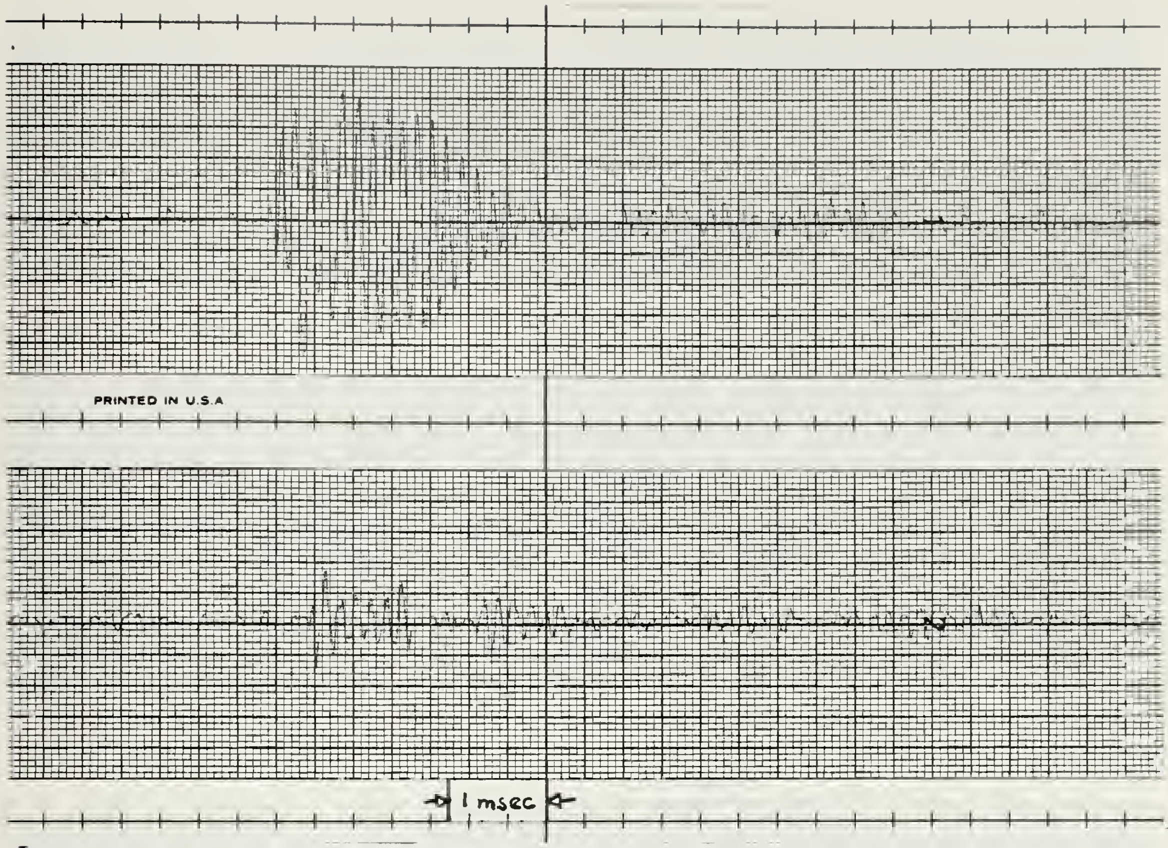

Figure 16. Expanded view of burst (f).
Upper track: Hydrophone 1.
Lower track: Hydrophone 0

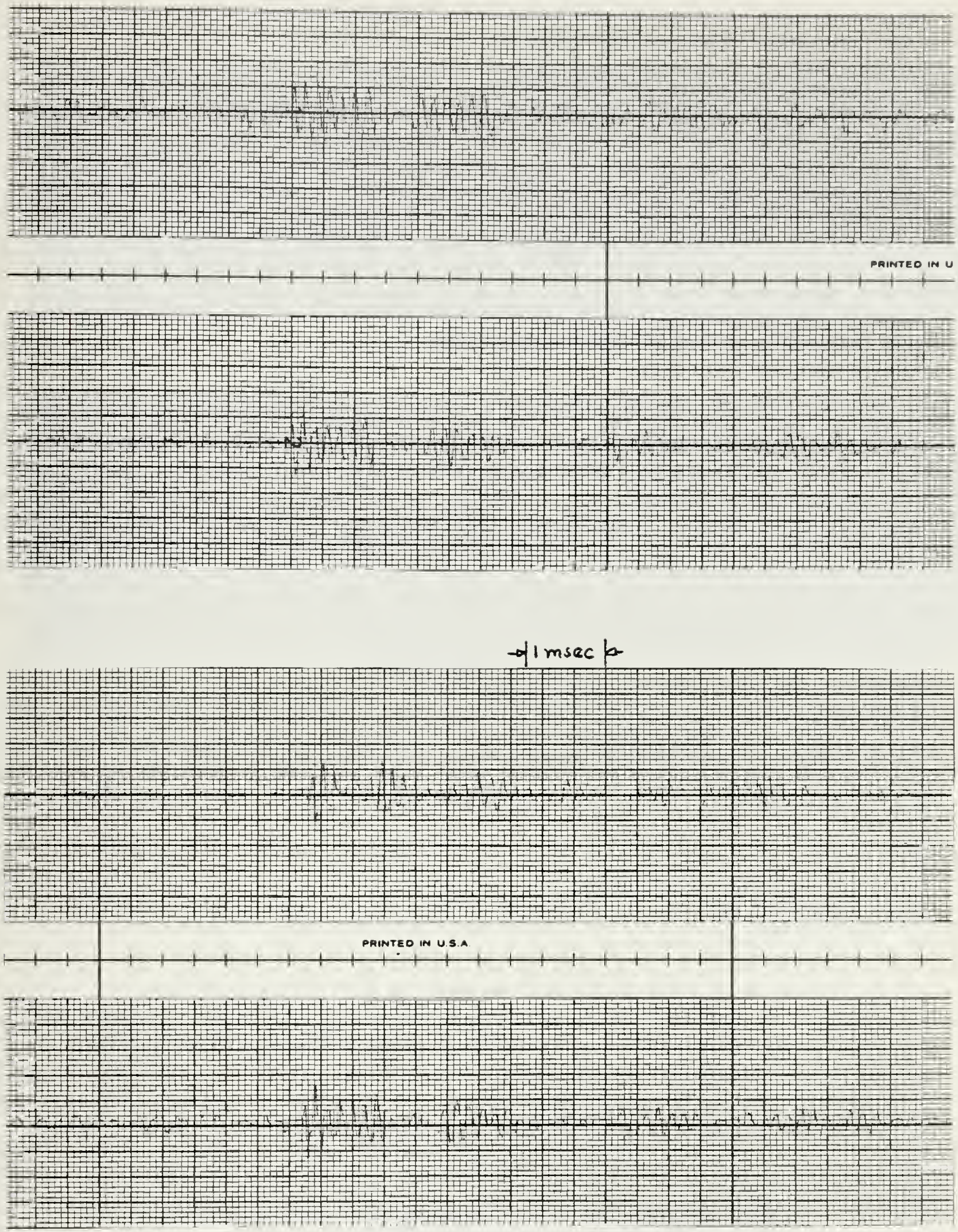

Figure 17. Expanded view of burst (f).
First track: Hydrophone 2.
Third track: Hydrophone 3.
Second and fourth track: Hydrophone 0

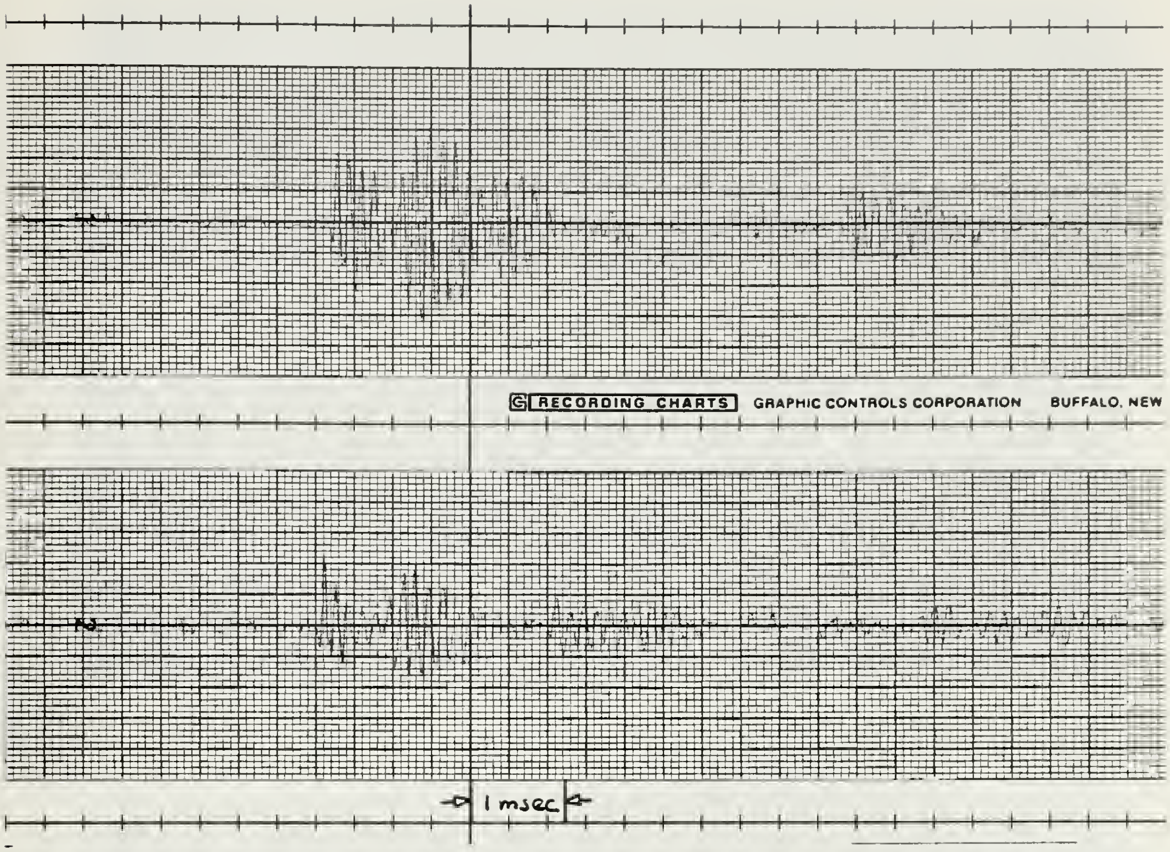

Figure 18. Expanded view of burst (g).
Upper track: Hydrophone 1.
Lower track: Hydrophone 0

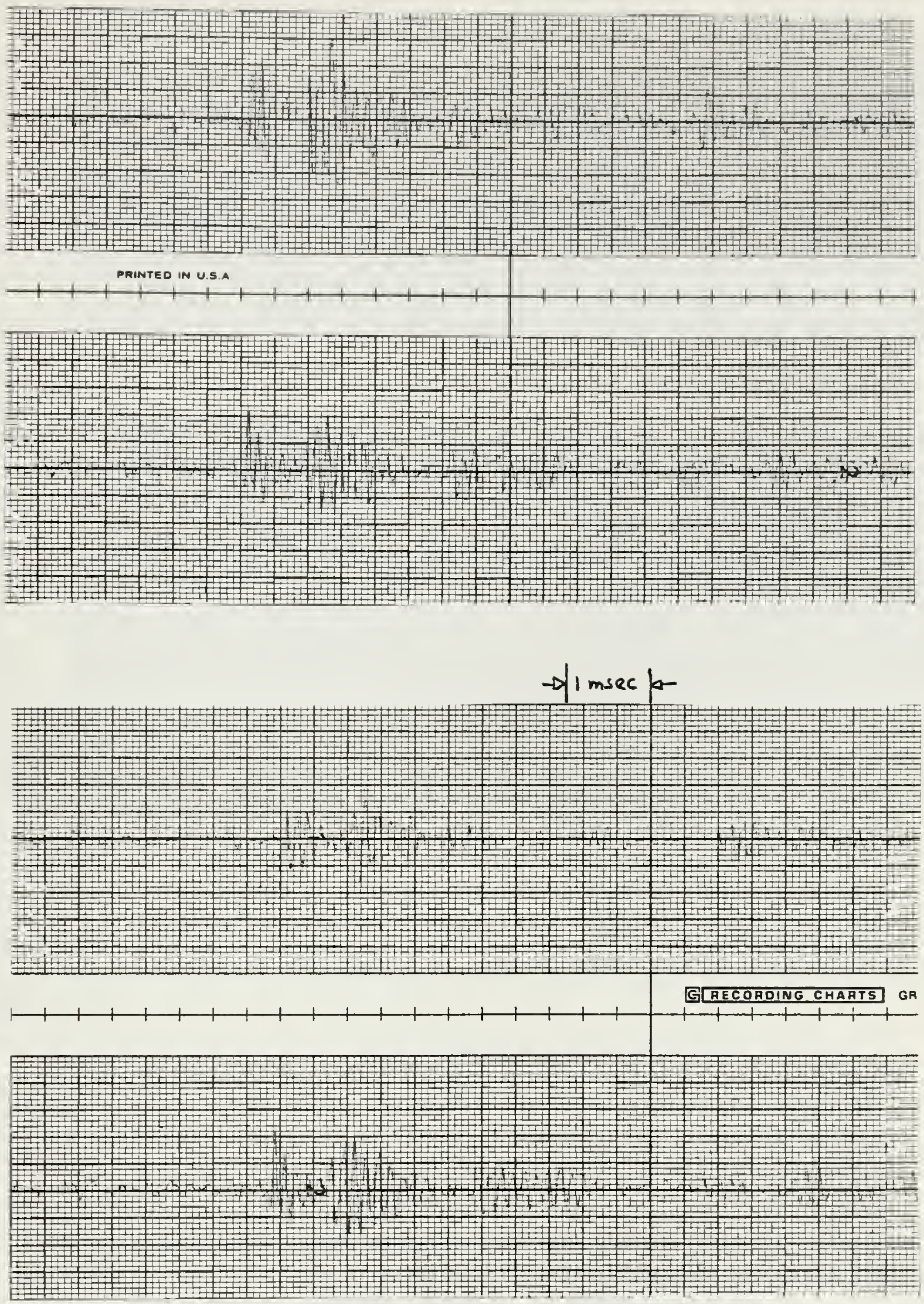

Figure 19. Expanded view of burst (g).
First track: Hydrophone 2.
Third track: Hydrophone 3.
Second and fourth track: Hydrophone 0

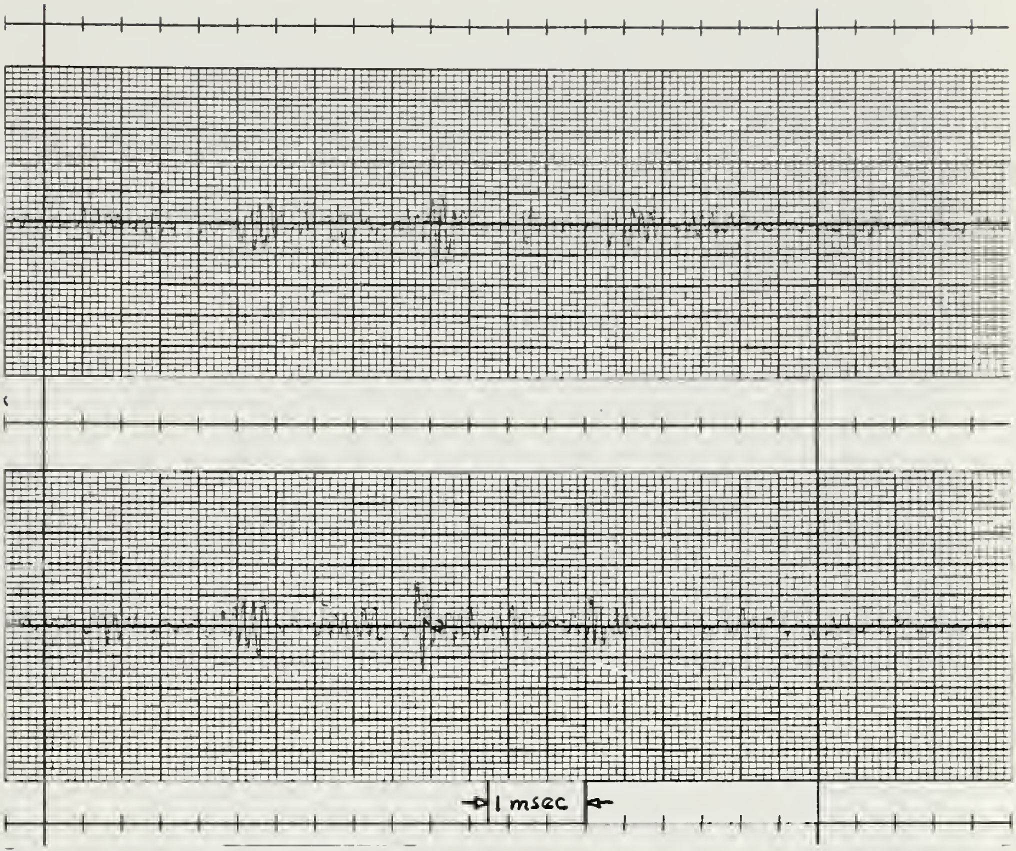

Figure 20. Expanded view of burst (h).
Upper track: Hydrophone 1.
Lower track: Hydrophone 0

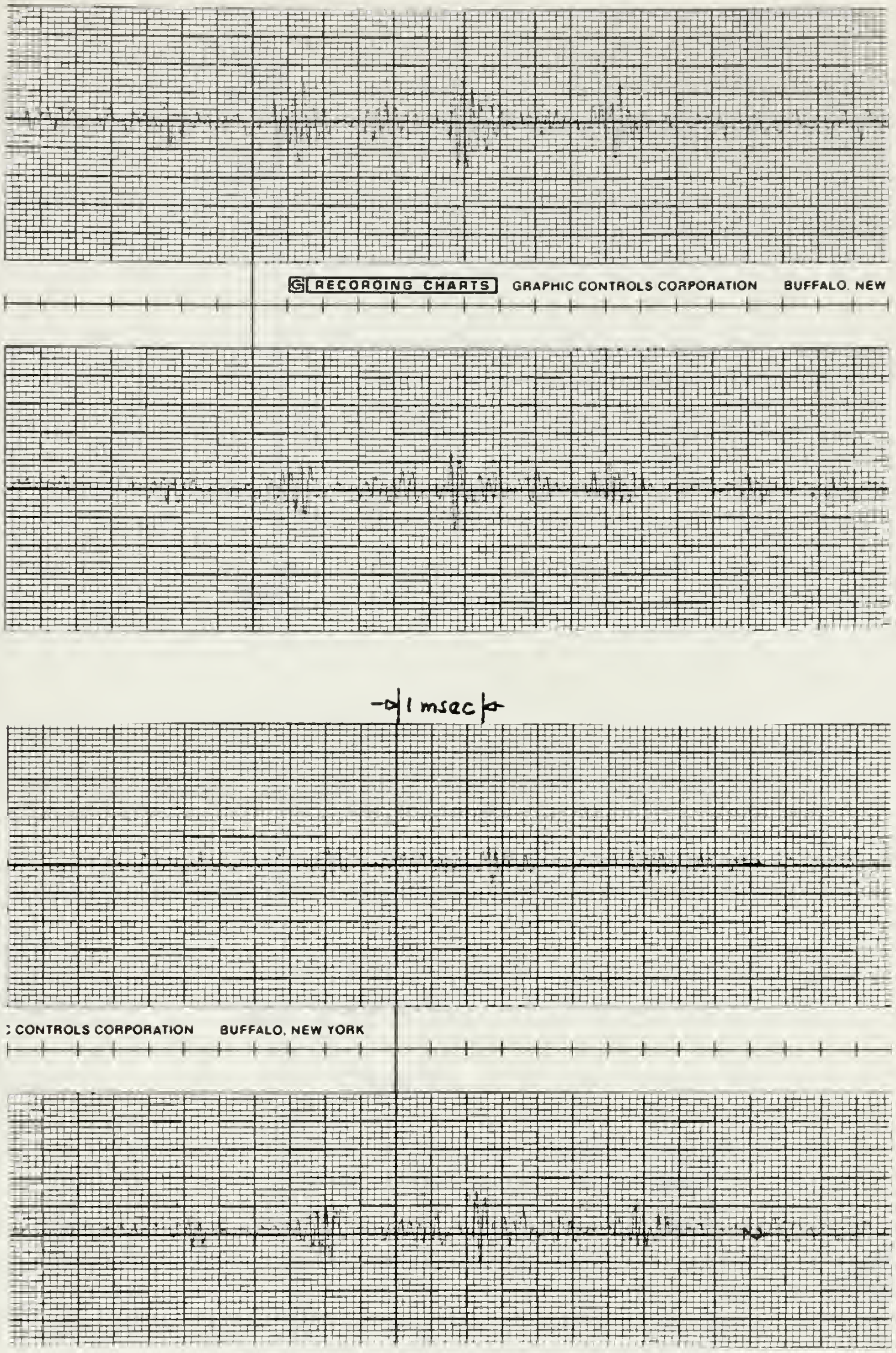

Figure 21. Expanded view of burst (h).
First track: Hydrophone 2.
Third track: Hydrophone 3.
Second and fourth track: Hydrophone 0

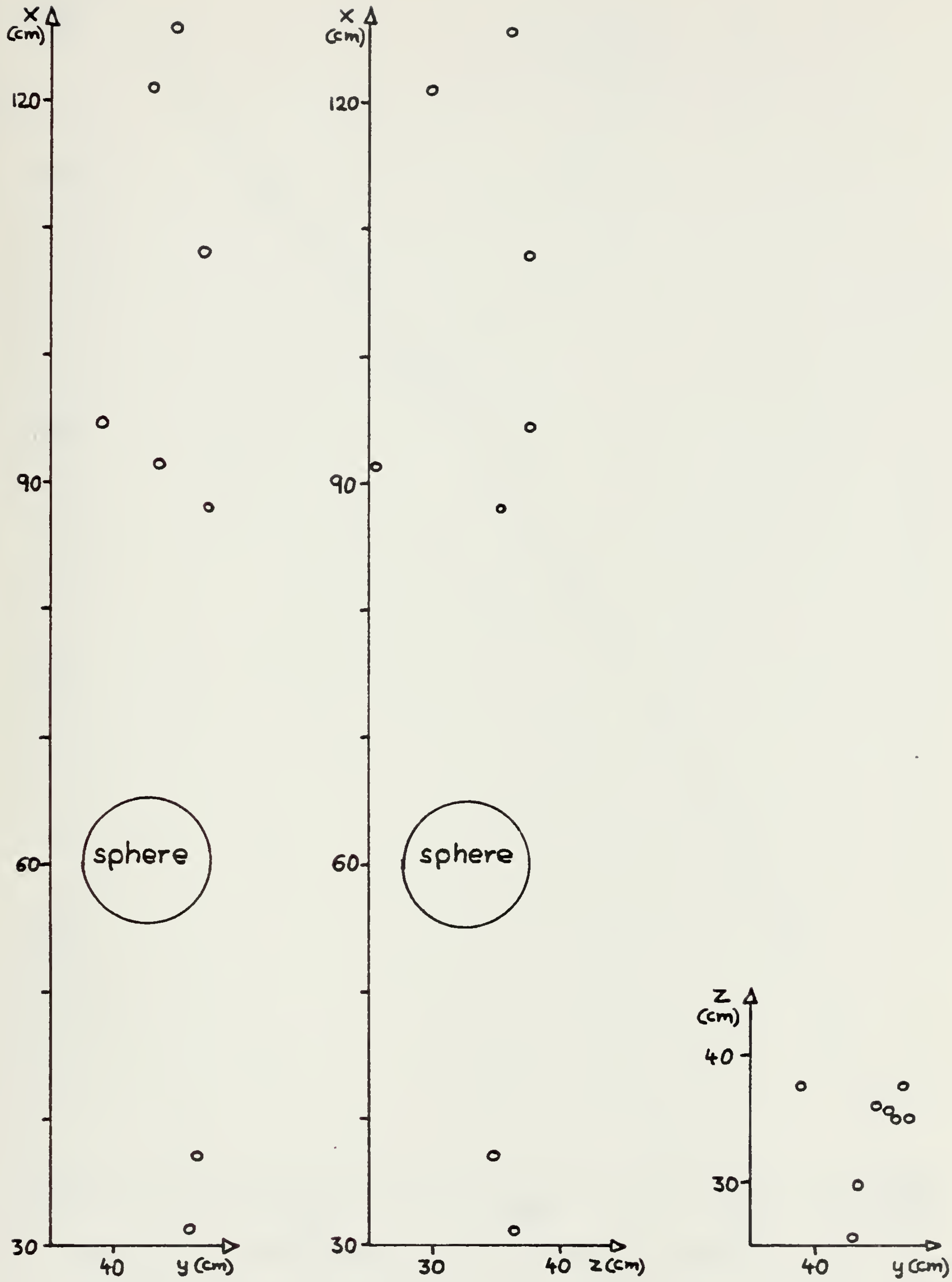

Figure 22. Location of the bursts for the run in Figs. 8-21

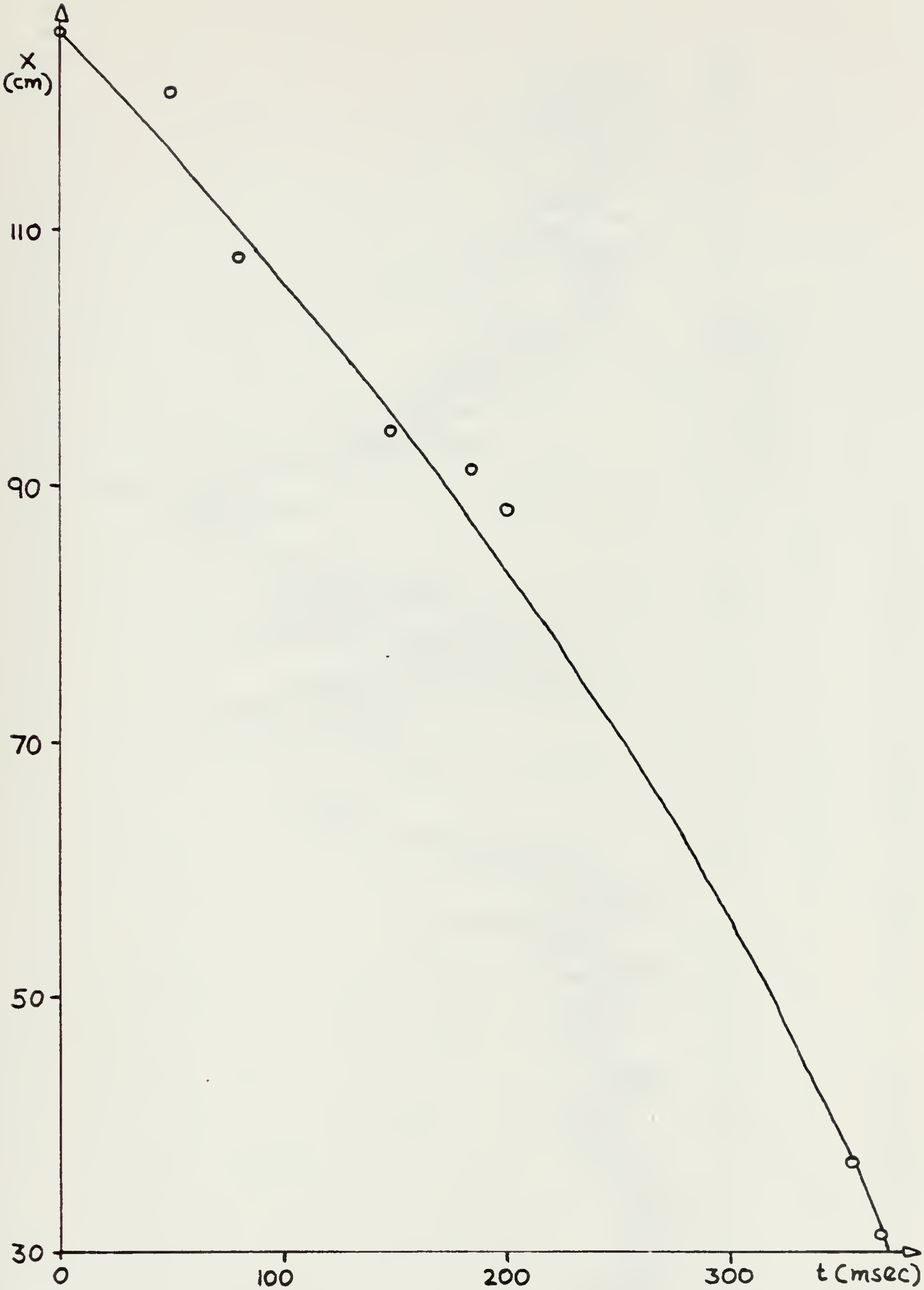

Figure 23. Trajectory of the bursts shown in Figs. 8-21

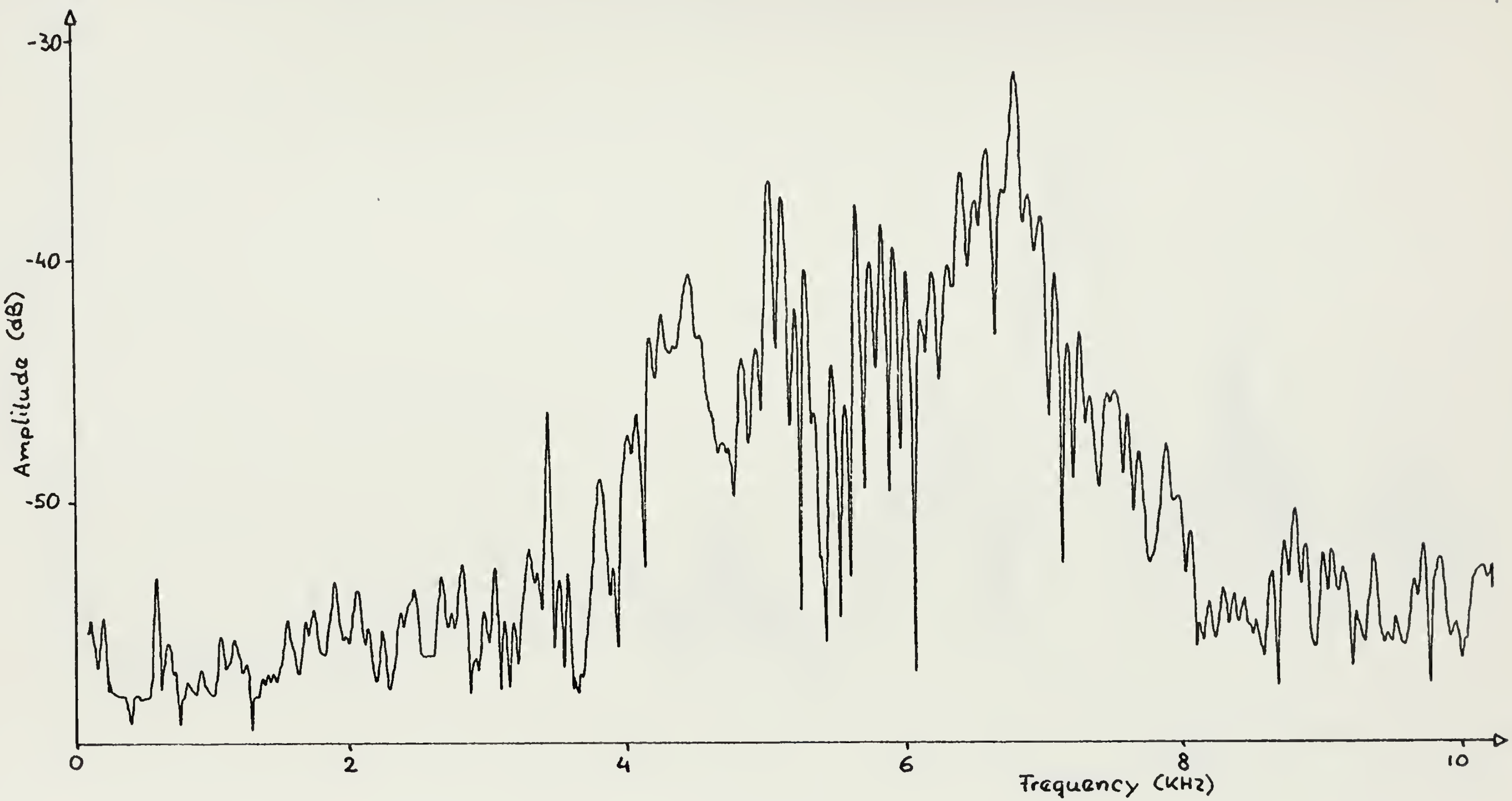

Figure 24. Frequency spectrum of burst (a)

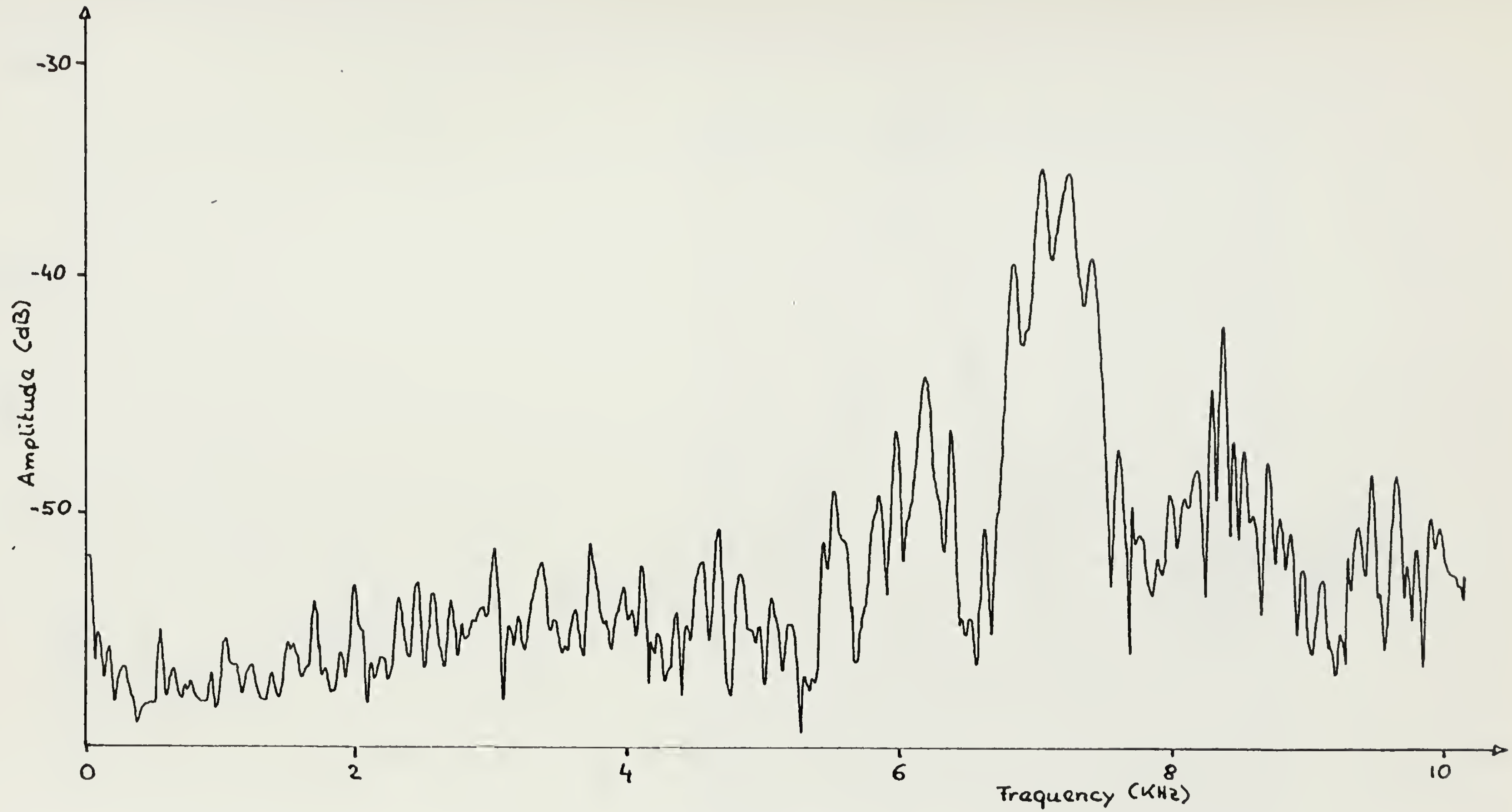

Figure 25. Frequency spectrum of bursts (e) and (f)

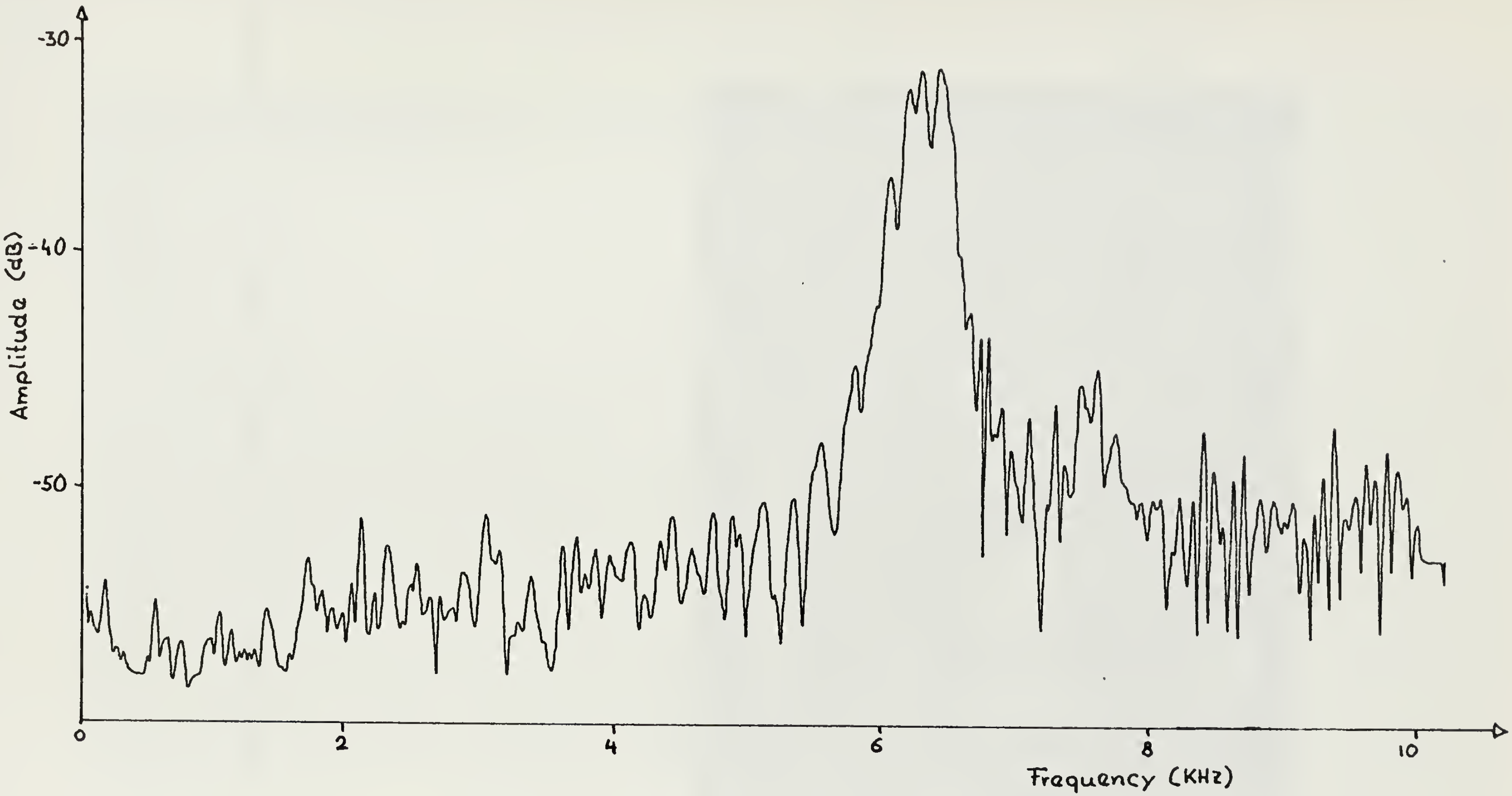

Figure 26. Frequency spectrum of bursts (g) and (h)

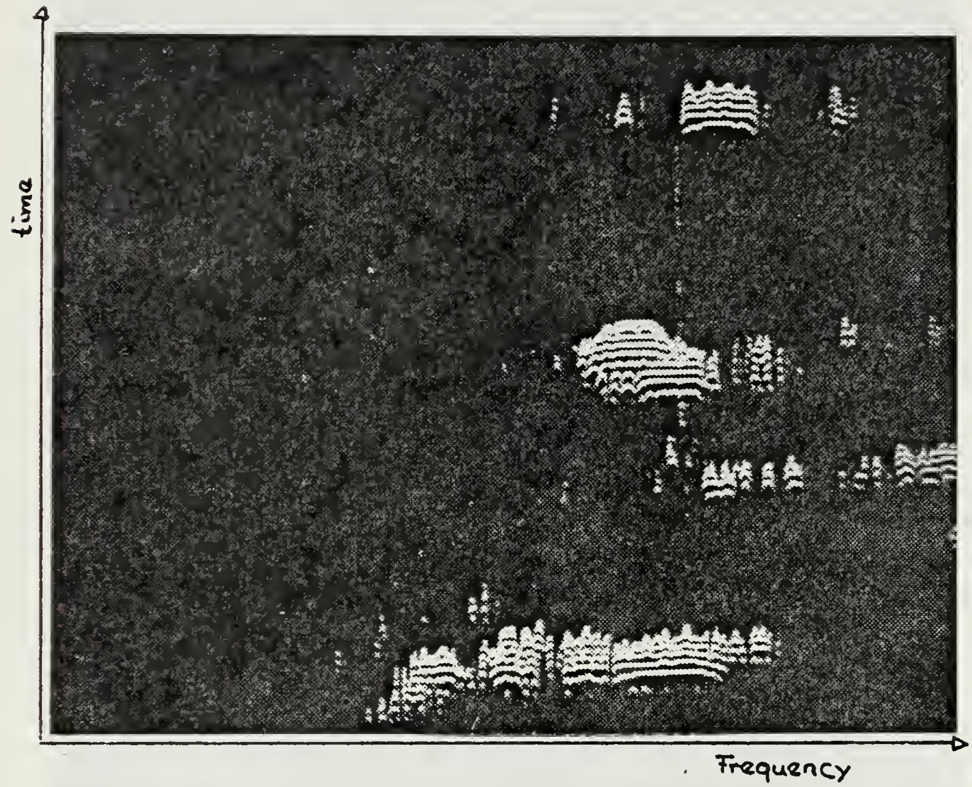

Figure 27. Waterfall display of the entire run of Figs. 8-9

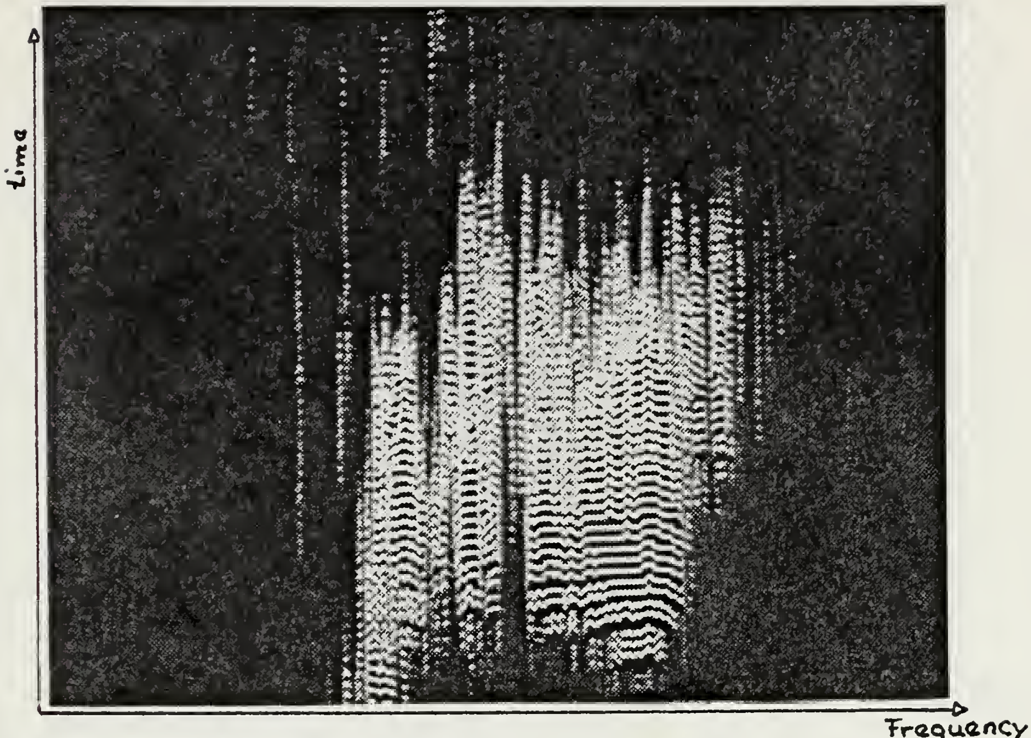

Figure 28. Waterfall display of bursts (a) - (b)

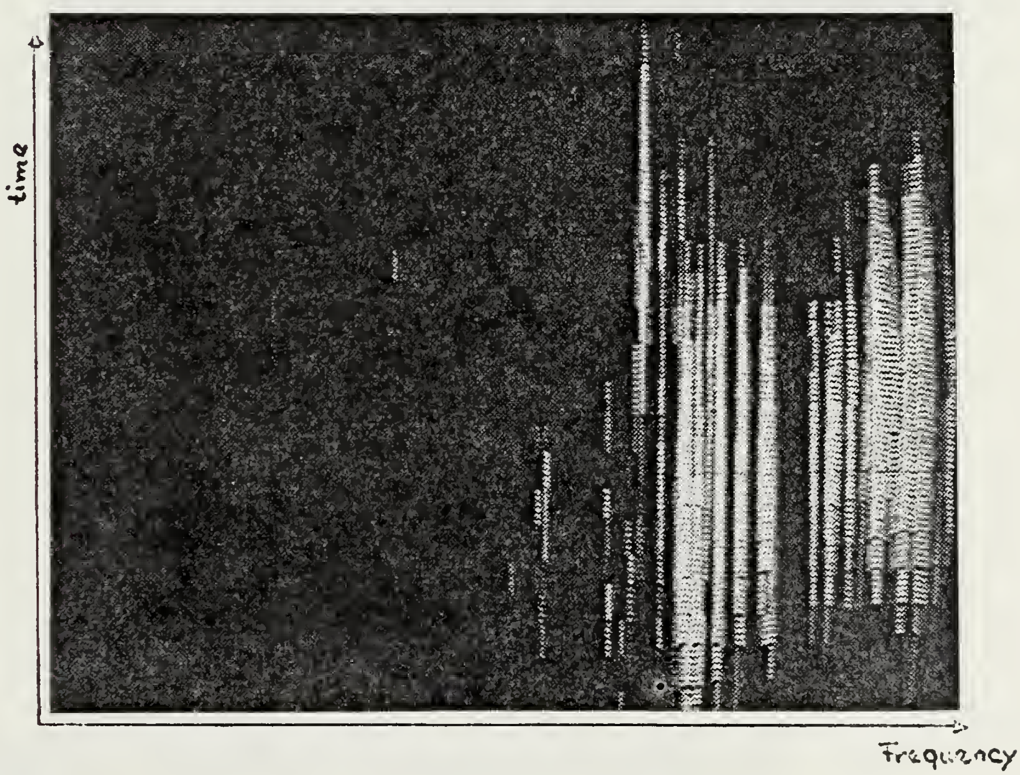

Figure 29. Waterfall display of burst (c)

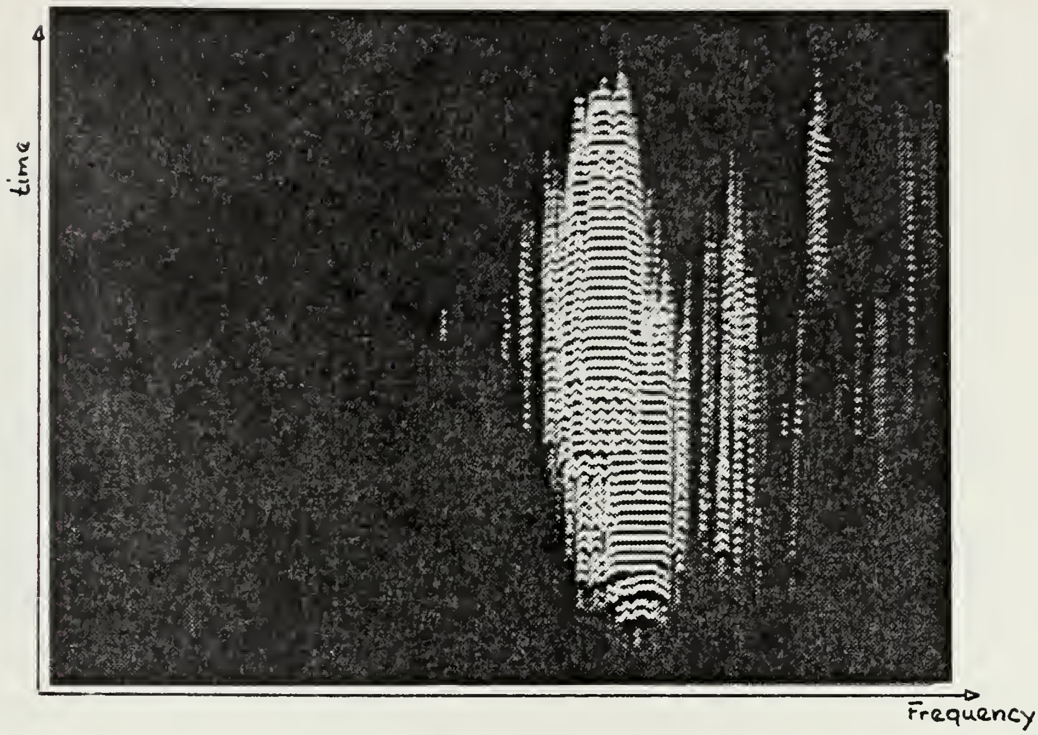

Figure 30. Waterfall display of bursts (d) - (f)

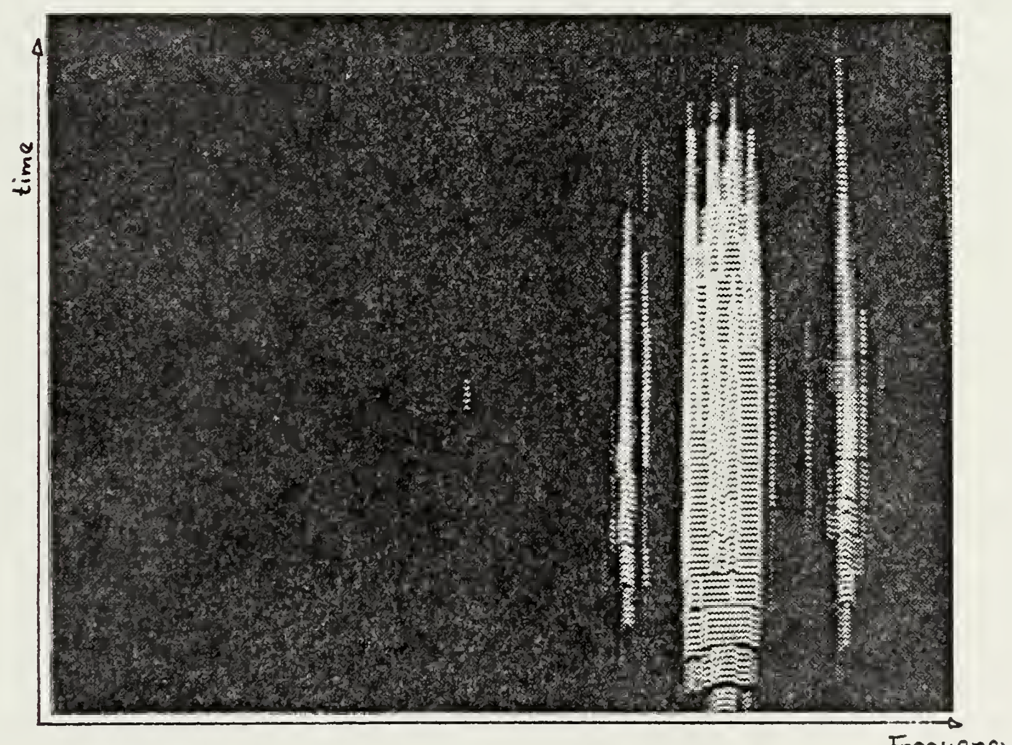

Figure 31. Waterfall display of bursts (g) - (h)

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